Cosmic origin of matter from proton stability

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with Admir Greljo, Anders Eller Thomsen

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Universität Basel

FNSNF

Proton Decay (or lack therof)

$\mathcal{L} = \sum_{\mathcal{O}}^{\infty} \mathcal{C}_{\mathcal{O}} \mathcal{O}(x)$ the SM global symmetries $\mathrm{U}(1)_B, \mathrm{U}(1)_L^3$ are **accidental** at $\dim\mathcal{O} \leq 4$

However, natural new physics **extensions** tend to predict proton decay, e.g. GUTs, Gravity, SMEFT ($\dim\mathcal{O} > 4$), ...

Proton lifetime lower bound:

$$\tau_p > 0.96 \times 10^{30} \mathrm{yr} \quad (90\,\%\ \mathrm{C.L.})$$

$p \to \mathrm{invisible}$ SNO+ '22

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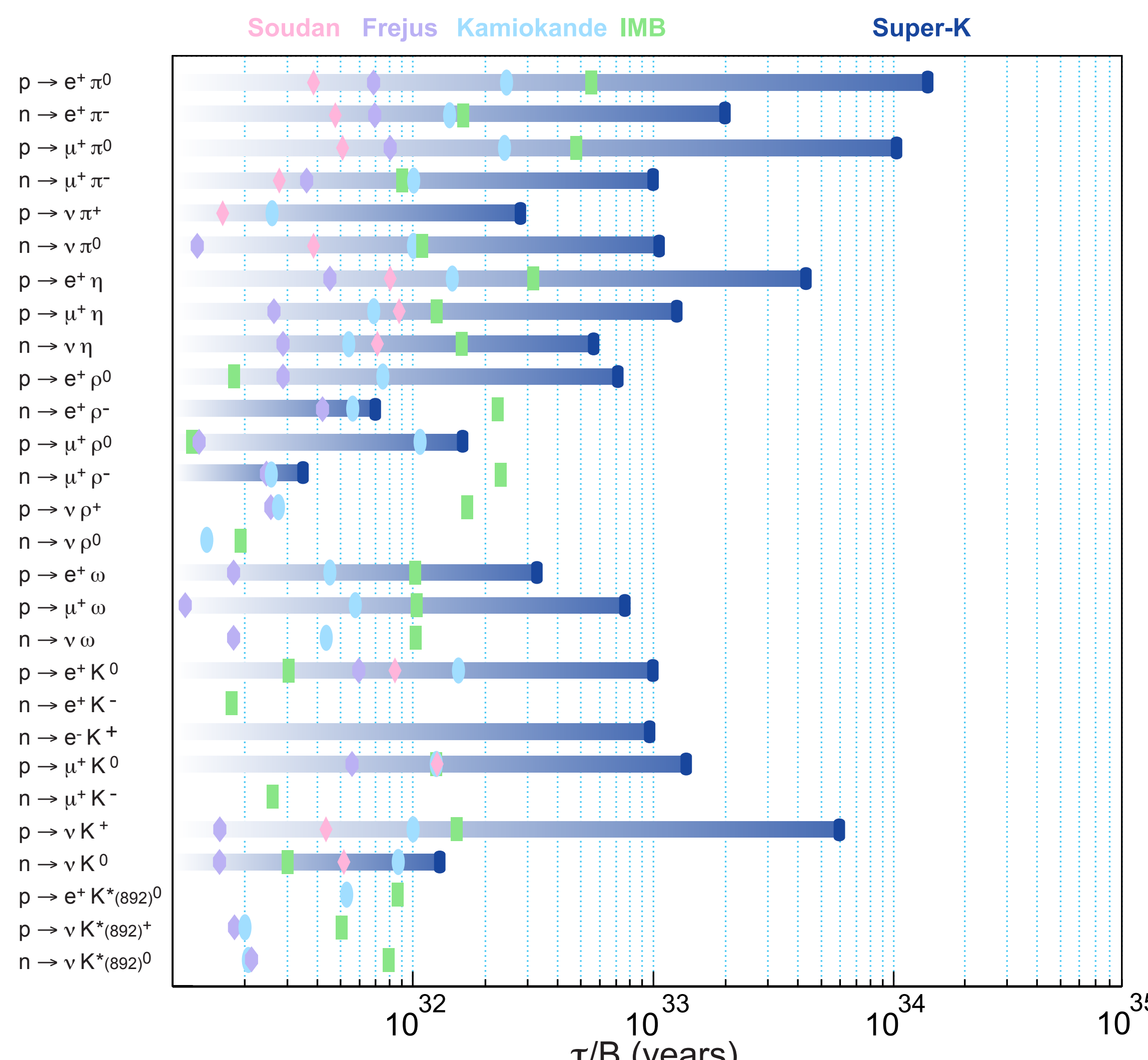
$$\Lambda_{\mathrm{GUT}} \gtrsim 10^{16} \mathrm{GeV}$$



Babu, Kearns, et al '13

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Can the proton be **absolutely** stable?

$\tau_p \to \infty$?

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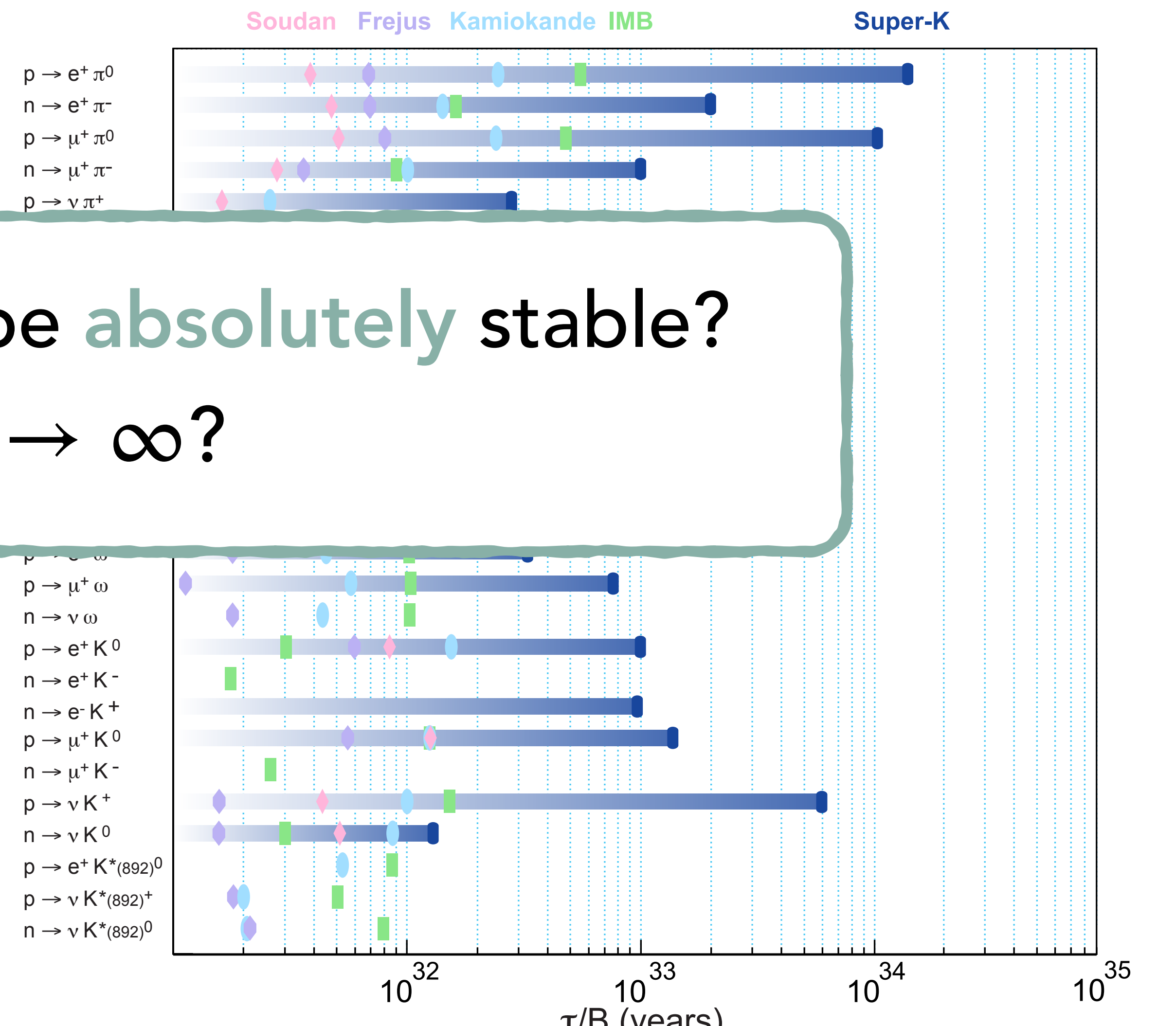

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What is this talk about

Purely academic: What if the proton is **absolutely** stable?

Davighi, Greljo, Thomsen '22

A model for **exact** proton **stability**

see also previous works
Babu, Gogoladze, Wang '03

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Greljo, XPD, Thomsen '25

Empirical evidence of **BSM**

Neutrino masses & mixing

$$\Delta m^2_{21} \simeq 7.49 \times 10^{-5}\,\mathrm{eV}^2\,,$$
$$\Delta m^2_{31} \simeq 2.5 \times 10^{-3}\,\mathrm{eV}^2$$

Nu-fit 6.0 '24

matter-antimatter asymmetry

$$\frac{n_b - n_{\bar{b}}}{n_\gamma} = (6.12 \pm 0.04) \times 10^{-10}$$

Planck 2018

Dark Matter

$$\Omega_{\mathrm{CDM}} h^2 = 0.1200 \pm 0.0012$$

Planck 2018

A model for proton stability

It all starts with $\mathrm{U}(1)_B$

A model for proton stability

If imposed globally

It all starts with $\mathrm{U}(1)_B$ → Gravity breaks it

↓ If made local

Broken by EW anomaly

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→ Local $\mathrm{U}(1)_{B-L}$

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↘ Local $\mathrm{U}(1)_{B-L}$

Not anomalous ✔

Anomaly cancelation: 3 RH Neutrinos

Realistic neutrino masses ✔

$$\mathcal{L}_{B-L} = \phi \bar{N}^c N + \bar{\ell}_L N \tilde{H} + \mathrm{H.c.}$$

Seesaw mechanism

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Exact proton stability

$$\mathrm{U}(1)_{3(B-L)} \rightarrow [q] = 1,\ [\phi] = 6$$

$$\mathrm{U}(1)_{B-L} \xrightarrow{\langle\phi\rangle \neq 0} \mathbb{Z}_6$$

discrete gauge symmetry in the IR

$$\mathbb{Z}_6\ :\ \phi \rightarrow e^{i\frac{2\pi n}{6}}\phi,\ n = 0,\ \ldots,\ 5 \qquad [q] = 1,\ [l] = [N] = 3$$

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SMEFT:

$qqql,\ \bar{l}dddH,\ \dots$

A model for proton stability

The **idea**: Davighi, Greljo, Thomsen '22

Gauge $\mathrm{U}(1)_{X_p} \xrightarrow{\langle\phi\rangle \gg \langle H\rangle} \mathbb{Z}_k$

Such that proton decay is forbidden in the SMEFT to all orders

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How: $3(B-L)$ Non-anomalous
$L_i - L_j$ general symmetry

$$\mathrm{U}(1)_{X_p} \to X_p = 3m(B-L) - n(3L_p - L)$$

p : specific lepton flavour $p = e, \mu, \tau$ $\quad$ $\mathrm{gcd}(m,\, n) = 1$

....

(*gcd): greatest common divisor

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$$\bar{\ell}_L e_R H,\, \bar{\ell}_L N \tilde{H} \sim \begin{pmatrix} \times & 0 & 0 \\ 0 & \times & \times \\ 0 & \times & \times \end{pmatrix}$$

$$\bar{N}^c N \phi_1 \sim \begin{pmatrix} 0 & \times & \times \\ \times & 0 & 0 \\ \times & 0 & 0 \end{pmatrix}$$

Scalar charges:

$$\begin{pmatrix} [\phi_1]_{X_p} \\ [\phi_2]_{X_p} \end{pmatrix} = \begin{pmatrix} 6m + n \\ 6m - 2n \end{pmatrix}$$

need two SM-singlet scalars for PMNS

$$\bar{N}^c N \phi_2 \sim \begin{pmatrix} 0 & 0 & 0 \\ 0 & \times & \times \\ 0 & \times & \times \end{pmatrix}$$

(*gcd): greatest common divisor

A model for proton stability

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A model for proton stability

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Consider the following **charges**: Davighi, Greljo, Thomsen '22

$$(m,\, n) = \big(3a+1,\, 9b+3\big), \quad \text{for} \quad (a,\, b) \in \mathbb{Z}^2$$

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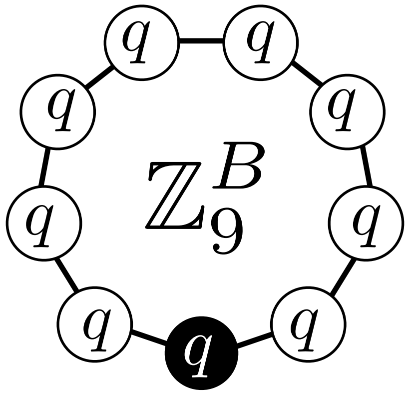
$$\mathrm{U}(1)_{X_p} \xrightarrow{\langle\phi_1\rangle,\langle\phi_2\rangle\neq 0} \mathbb{Z}_9^B$$

	Fields	$\mathrm{U}(1)_{X_p}$	$\mathbb{Z}_9 \subseteq \Gamma$
Quarks	$q_i,\, u_i,\, d_i$	m	1
Specific leptons	$\ell_p,\, e_p,\, N_p$	$-2n-3m$	0
Common leptons ($q \neq p$)	$\ell_q,\, e_q,\, N_q$	$n-3m$	0
Higgs	H	0	0
New scalars	ϕ_1	$6m+n$	0
	ϕ_2	$6m-2n$	0

$\mathbb{Z}_9^B$–singlets



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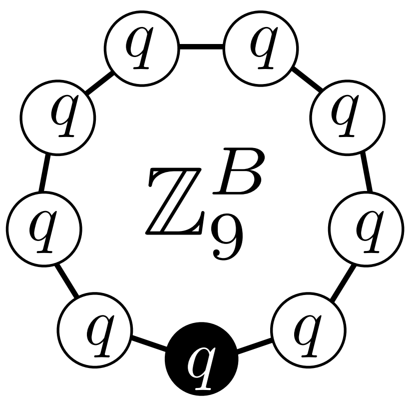

Davighi, Greljo, Thomsen '22

Exact discrete gauge symmetry **unbroken** in the **IR**

$$\mathbb{Z}_9^B\text{-singlet}: \quad (qqq)(qqq)(qqq)$$

SMEFT selection rule

$$\Delta B = 0 \pmod 3$$

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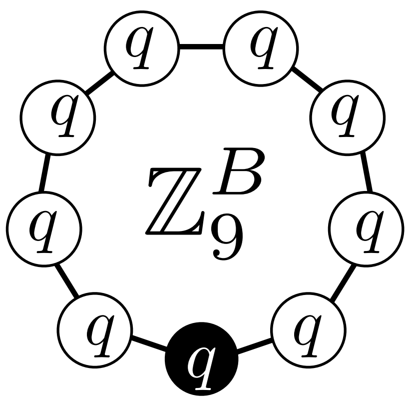

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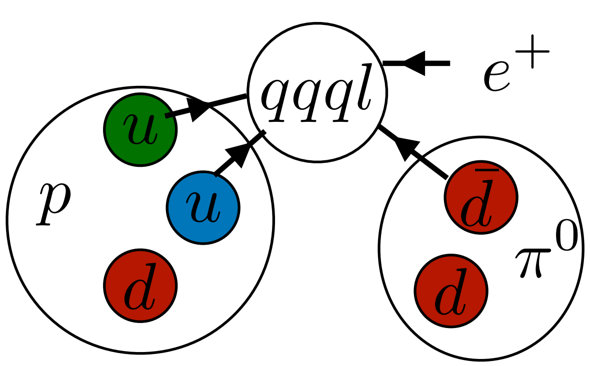
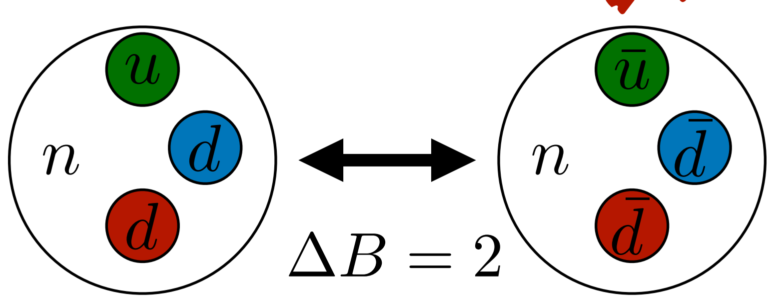
proton decay

$$\Delta B = 1$$



neutron-antineutron oscillations

$$(\bar{q}^c q)(\bar{q}^c q)(\bar{q}^c q)$$



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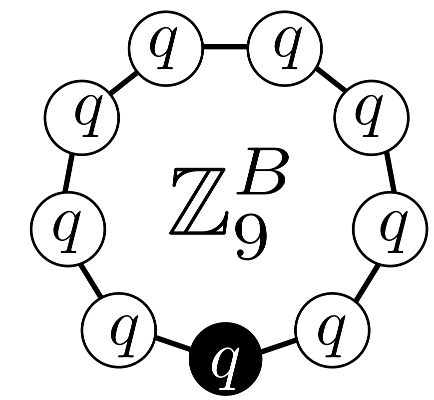

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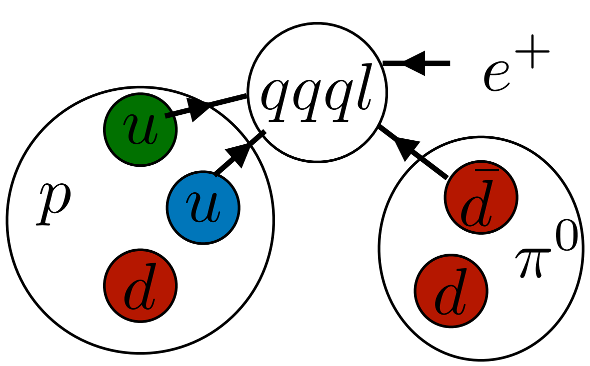
proton decay

$$\Delta B = 1$$



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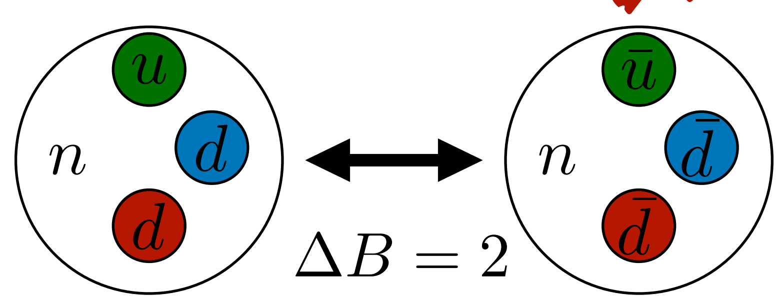
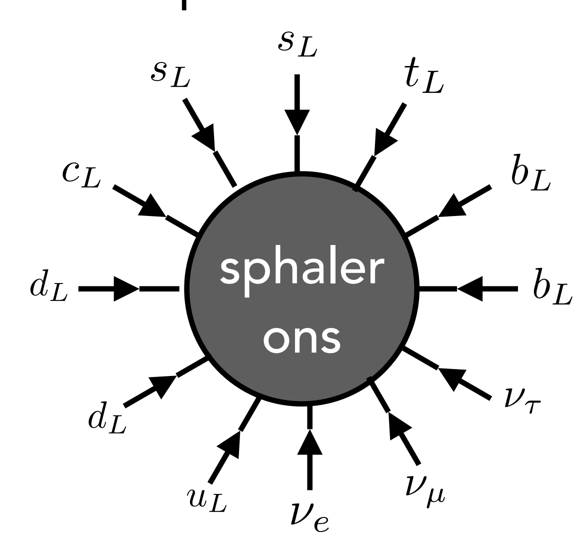


Sphalerons



$$\Delta B = 3$$

Neutrino Masses

+ p-permutations

$$M_N \sim \langle\phi_1\rangle \begin{pmatrix} 0 & \times & \times \\ \times & 0 & 0 \\ \times & 0 & 0 \end{pmatrix} + \langle\phi_2\rangle \begin{pmatrix} 0 & 0 & 0 \\ 0 & \times & \times \\ 0 & \times & \times \end{pmatrix} \qquad Y_N \sim \begin{pmatrix} \times & 0 & 0 \\ 0 & \times & \times \\ 0 & \times & \times \end{pmatrix}$$

majorana phases

The seesaw

Minkowski '77, Gell-Mann, Ramond, Slansky '79, Yanagida '80, Mohapatra, Senjanovic '80, Schechter, Valle '80

$$m_\nu = -\langle H\rangle^2 Y_\nu^* M_N^{-1} Y_\nu^\dagger = U^T \hat{m}_\nu U$$

$$U = V_{\rm PMNS}\,{\rm diag}(e^{i\alpha/2},\, e^{i\beta/2},\, 1)$$

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The **flavour-specific** local symmetry imposes the following tree-level **condition**:

The **p-minor** $= 0$

$$m_\nu^{ii} \times m_\nu^{jj} - (m_\nu^{ij})^2 = 0\,, \quad \text{for } i \neq j \neq p$$

Greljo, XPD, Thomsen '25

e-specific case $\Longrightarrow 0 = \dfrac{1}{m_3} s_{13}^2 + \dfrac{e^{i(\beta+2\delta_{\rm CP})}}{m_2} s_{12}^2 c_{13}^2 + \dfrac{e^{i(\alpha+2\delta_{\rm CP})}}{m_1} c_{12}^2 c_{13}^2$

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- Triangle equation in the complex plane
- Triangle inequality ⇒ **lower limit** on the lightest neutrino

e-specific case

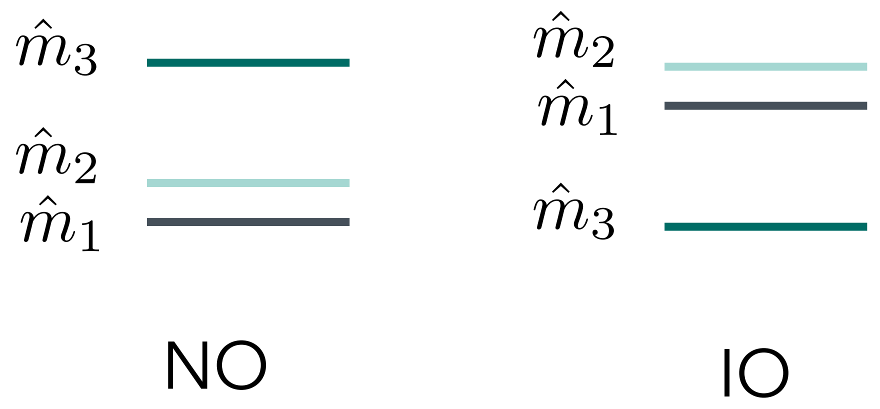
$$\frac{|s_{13}|^2}{m_3} \leq \frac{|s_{12}^2 c_{13}^2|}{m_2} + \frac{|c_{12}^2 c_{13}^2|}{m_1}$$

Neutrino Masses

e-specific case $\implies 0 = \frac{1}{m_3} s_{13}^2 + \frac{e^{i(\beta + 2\delta_{\text{CP}})}}{m_2} s_{12}^2 c_{13}^2 + \frac{e^{i(\alpha + 2\delta_{\text{CP}})}}{m_1} c_{12}^2 c_{13}^2$

Six scenarios: $p = e, \mu, \tau \times$ two orderings, but only **three** are consistent with experimental data:

- e-specific IO
- μ-specific NO
- τ-specific NO



If m_ν and δ_{CP} are **known** we can make a **prediction** on the Majorana phases

*Complex triangle equations have a second conjugate solution

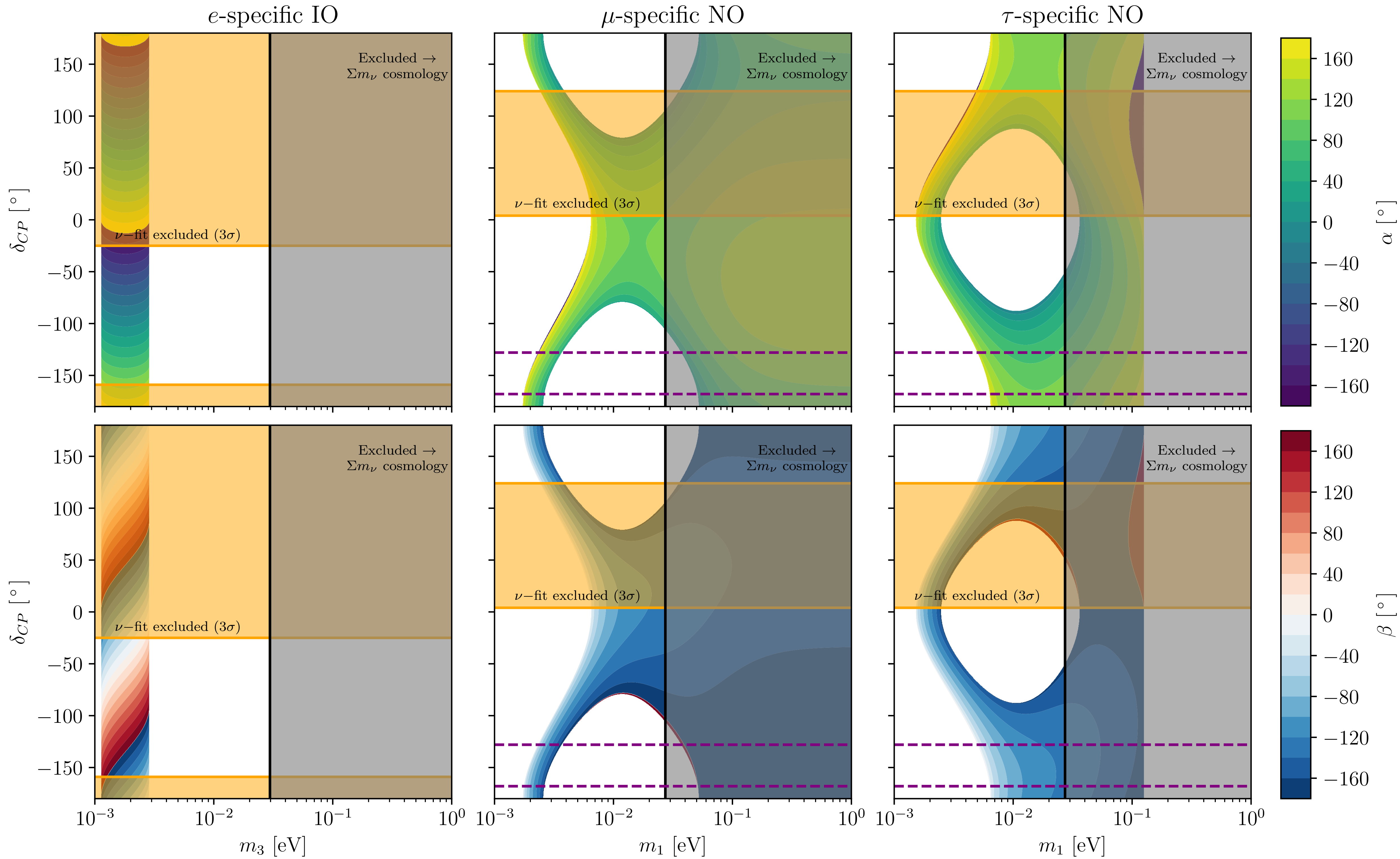
$\alpha \to -\alpha - \arg c_1$

$\beta \to -\beta - \arg c_2$

c_1, c_2: the sides of the triangle

Neutrino Masses

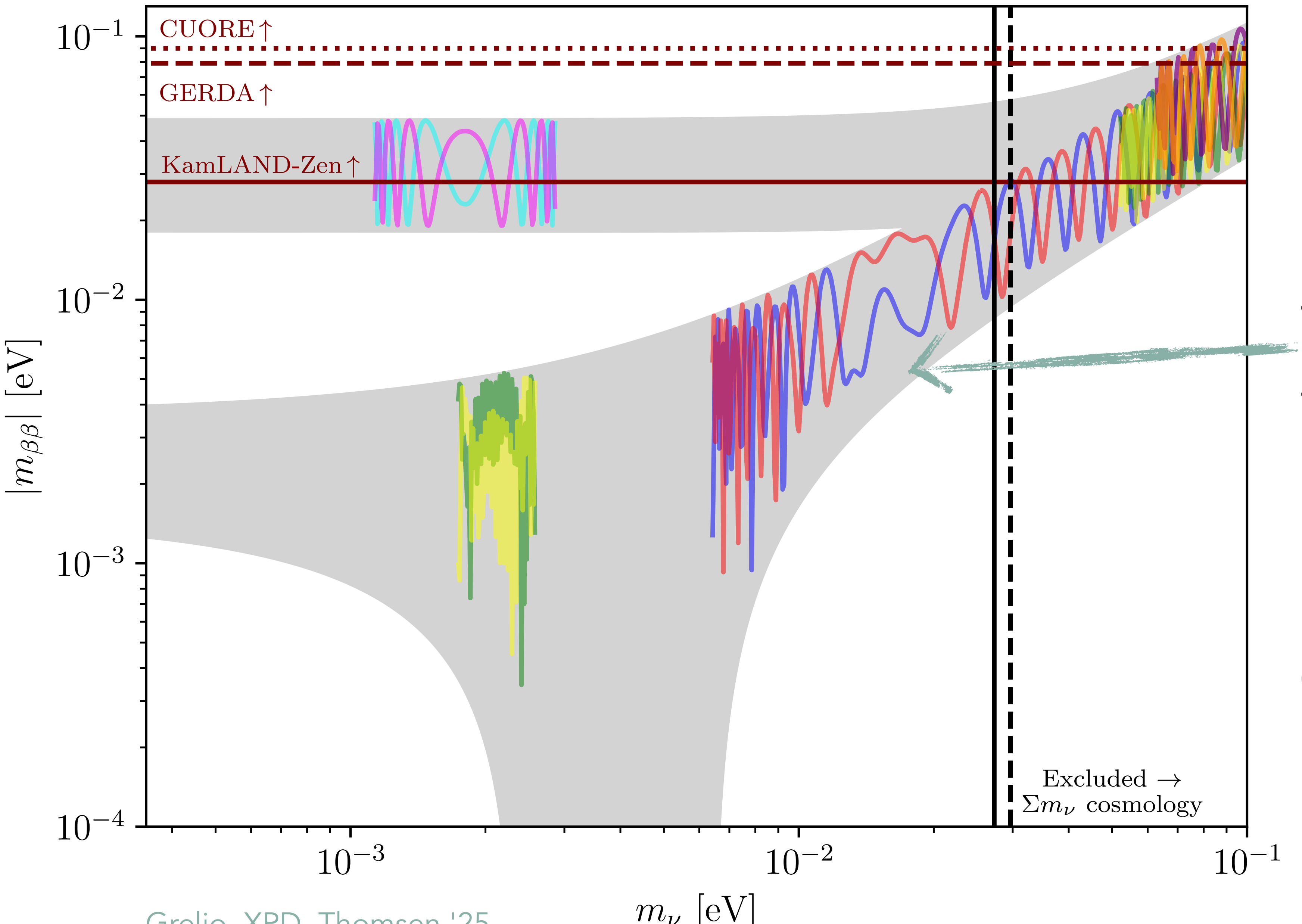
Greljo, XPD, Thomsen '25



Neutrino Masses

The future neutrino program is crucial!

Given δ_{CP} we can predict $|m_{\beta\beta}|$ as a function of m_ν

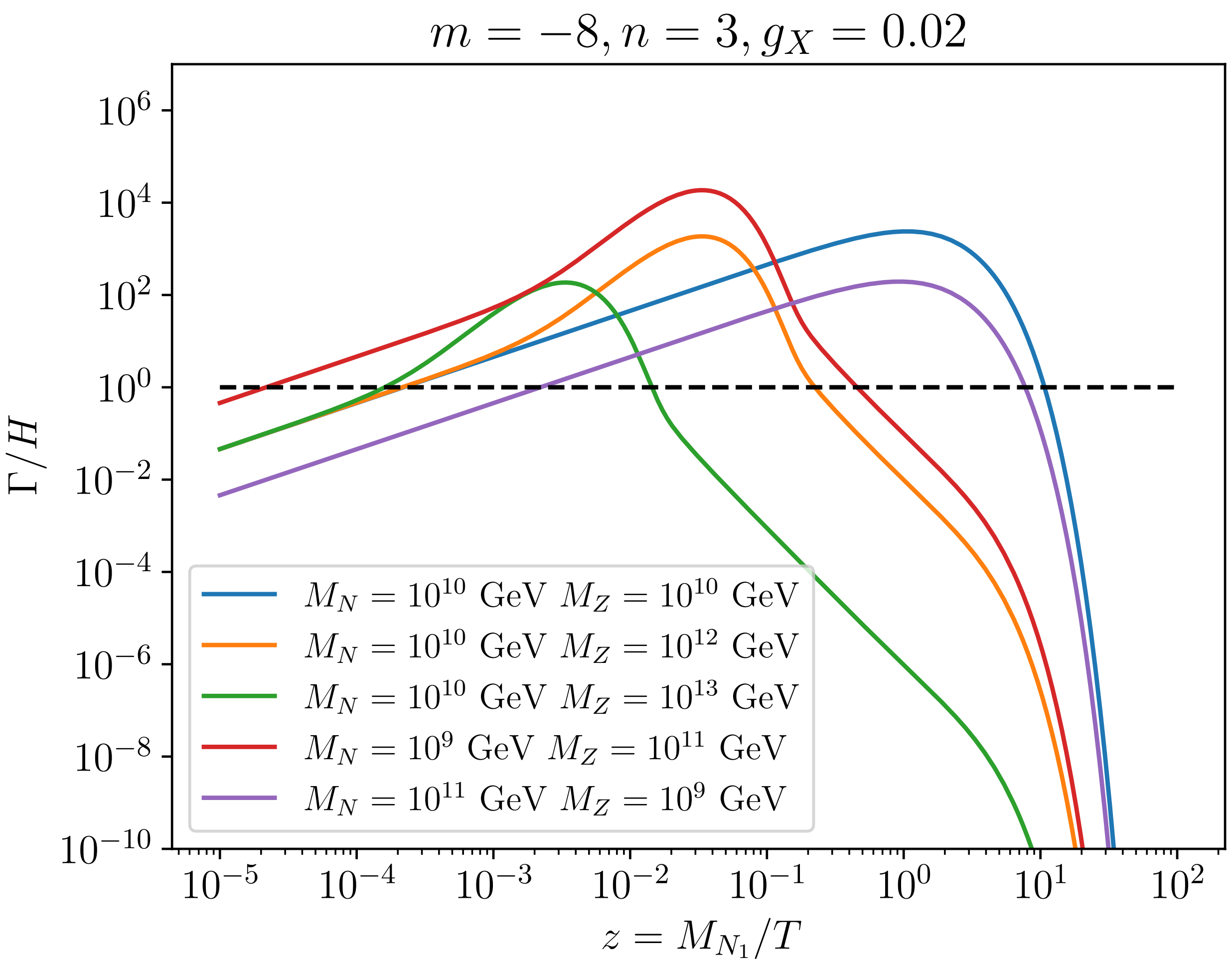


Greljo, XPD, Thomsen '25

Two solutions to the triangle equations

Models clearly **distinguishable** if the Dirac phase is known to $\delta_{CP} \sim 50^\circ$

The origin of matter: Leptogenesis



Z' Interactions must **decouple** at $\Gamma < H|_{T=M_{N_1}}$, for N_1 to decay **out of equilibrium**

$$M_{Z'} \gtrsim 10^2 M_{N_1}$$

*analogous to light neutrinos in the SM and EW interactions

See also Plümacher '96

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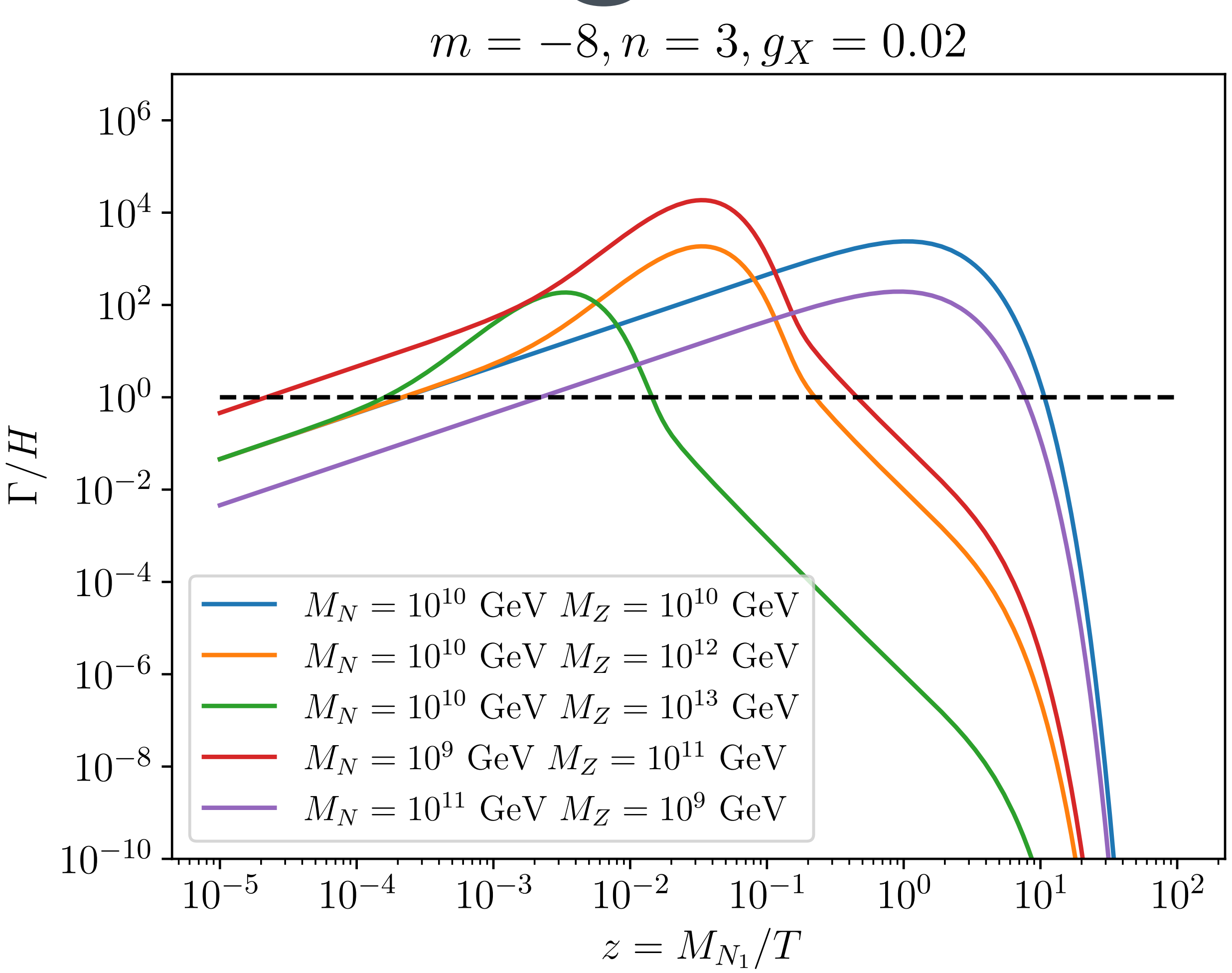

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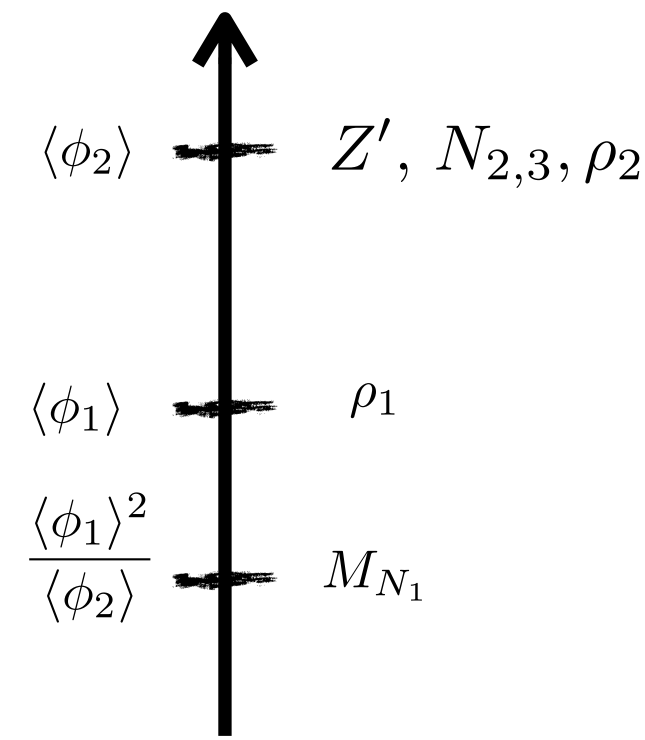
Assuming $\lambda \sim y_N \sim g_X \sim \mathcal{O}(1)$

If $\langle \phi_1 \rangle \ll \langle \phi_2 \rangle \rightarrow M_{N_1} \ll M_{N_{2,3}}$

Seesaw structure for RH neutrinos

$$M_N \sim \langle \phi_1 \rangle \begin{pmatrix} 0 & \times & \times \\ \times & 0 & 0 \\ \times & 0 & 0 \end{pmatrix} + \langle \phi_2 \rangle \begin{pmatrix} 0 & 0 & 0 \\ 0 & \times & \times \\ 0 & \times & \times \end{pmatrix}$$

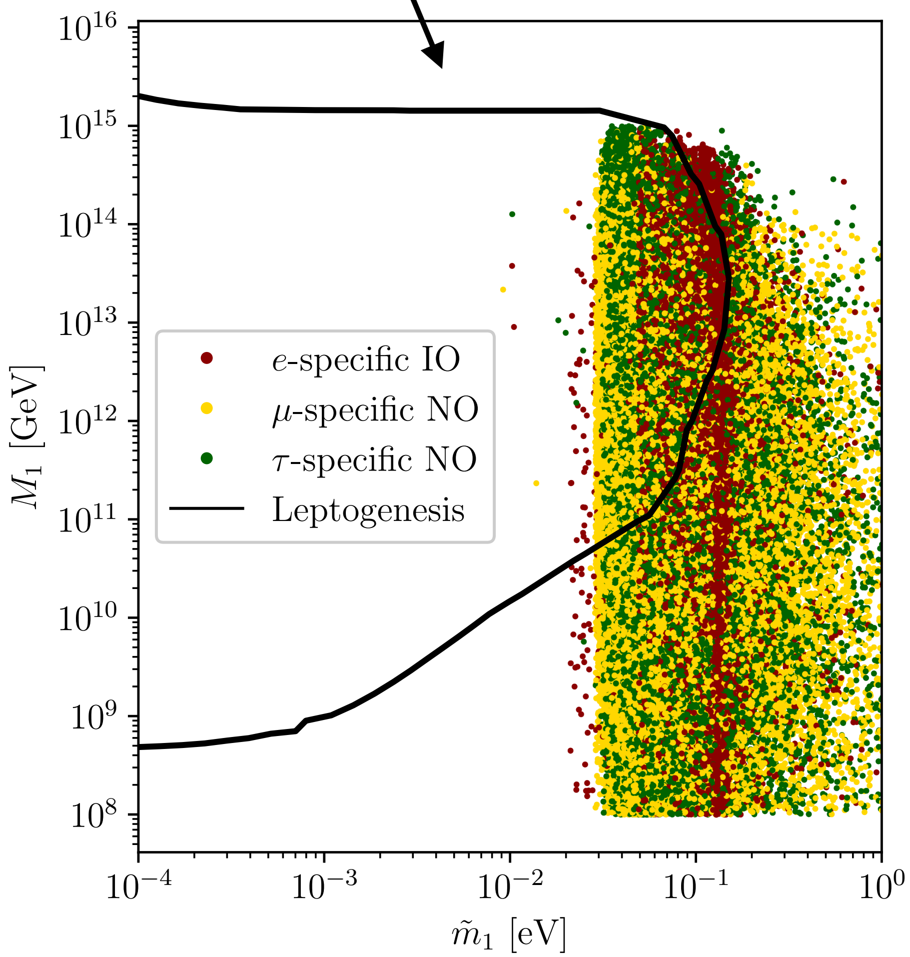


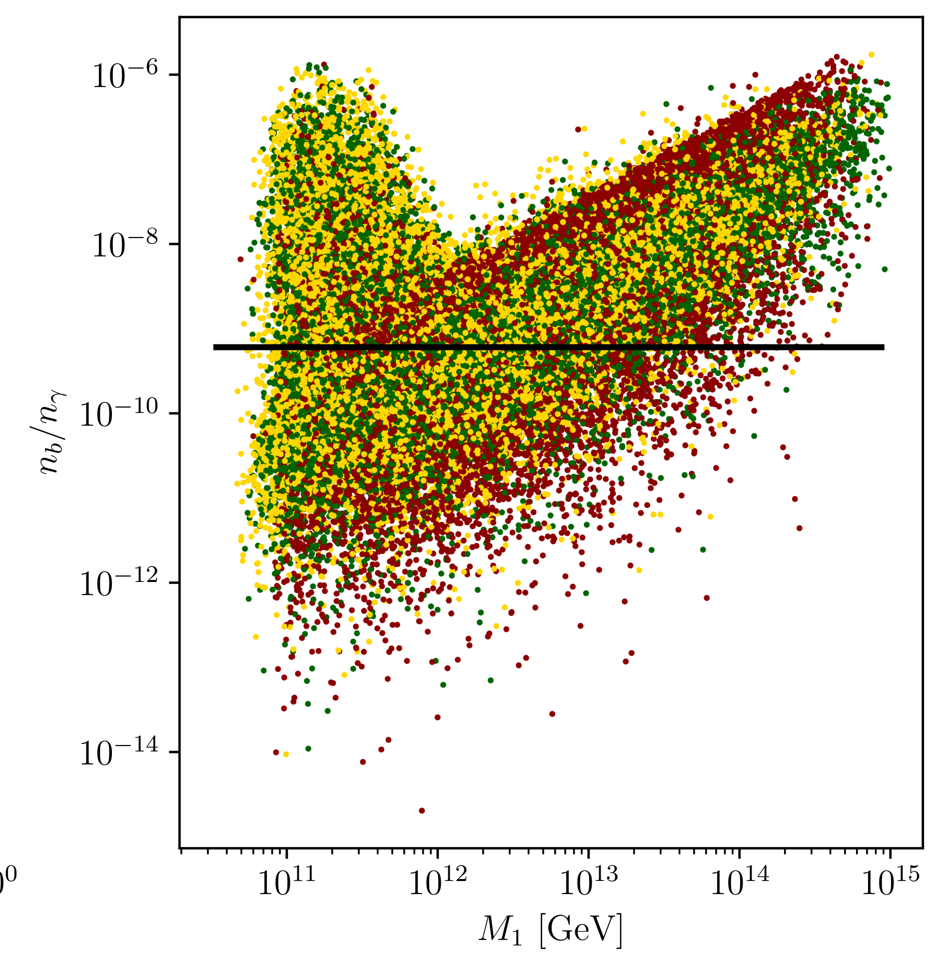
The origin of matter: Leptogenesis

Leptogenesis happens **only** via N_1 ($N_{2,3}$ decays washed-out & Z' keep them in eq.)

Baryogenesis via minimal thermal leptogenesis

Giudice, Notari, Raidal, Riotto, Strumia '03





$$\tilde{m}_1 = v_{\rm EW}^2 \frac{(Y_N^\dagger Y_N)_{11}}{M_{N_1}}$$

Triangle inequalities

⇒ lower bound neutrino mass

⇒ Strong-washout regime

Greljo, XPD, Thomsen '25

Nu-fit 6.0 '24

UV scan of parameters: all points within 3σ of neutrino **mass splittings** and **mixings**

The origin of matter: Dark Matter

Two complex scalars and one gauge symmetry $\mathrm{U}(1)_{X_p}$

$$\begin{pmatrix} [\phi_1]_{X_p} \\ [\phi_2]_{X_p} \end{pmatrix} = \begin{pmatrix} 6m + n \\ 6m - 2n \end{pmatrix}$$

Scalar charges are coprimes ⇒
Accidental global symmetry in the potential

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φ_X: eaten by the Z'

Two Goldstone bosons

a: (pseudo-)Nambu-Goldstone Boson

$$\begin{pmatrix} a \\ \varphi_X \end{pmatrix} = \begin{pmatrix} c_\varphi & -s_\varphi \\ s_\varphi & c_\varphi \end{pmatrix} \begin{pmatrix} a_1 \\ a_2 \end{pmatrix} ,$$

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a: is a **majoron**, the Goldstone boson associated to the breaking of **global** $\mathrm{U}(1)_{B-L}$

Tree-level coupling to RH neutrinos: $\mathcal{L} \supset i \frac{a}{f_a} \bar{N}^c M_N N$

Couplings to **LH** neutrinos: $\mathcal{L} \sim i \frac{a}{f_a} \frac{(m_\nu)_{ij}}{v_{\mathrm{EW}}^2} \bar{\ell}_i^c \tilde{H}^c H^\dagger \ell_j$

Chikashige, Mohapatra, Peccei '80, '81, Gelmini, Roncadelli '81, Schechter, Valle '82

The origin of matter: Dark Matter

Mass origin: gravity explicit breaking of the global symmetry

See also other ways: Hambye, Frigerio, Masso '11 , de Giorgi, Merlo, XPD, Rigolin '23

pseudo-Nambu Goldstone Boson **majoron**

$$V_{\text{grav.}} = (4\pi)^2 \frac{\eta}{M_{\text{Pl}}^{|s|+|t|-4}} \phi_1^{[s]} \phi_2^{[t]} + \text{h.c.} \qquad m_a^2 = 8\pi^2 |\eta| M_{\text{Pl}}^2 \frac{v_1^{|s|-2} v_2^{|t|}}{(\sqrt{2} M_{\text{Pl}})^{|s|+|t|-2}} \left(s^2 + \frac{v_1^2}{v_2^2} t^2 \right).$$

At what dimension?

The origin of matter: Dark Matter

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At what dimension? Lowest dimensional operator not forbidden by $\mathrm{U}(1)_{X_p}$

Leading Planck-suppressed operator $\min(|s| + |t|)$

a \ b	-5	-4	-3	-2	-1	0	1	2	3	4	5
-5		15		17		19				23	
-4	7		6	13	7	15	8	17	9	19	10
-3		11		9		11		13		15	
-2	7	11	4		3	7	4	9		13	8
-1		11		5				7		13	
0	7	11	4	5				7	5	13	8
1		11		7		5		7		13	
2		13	6	11	5	9	4		5	13	8
3		17				13		11		13	
4	11	21	10	19	9	17	8	15	7		8
5		25		23		21		19		17	

*colors see backup

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5		25		23		21		19		17	

*colors see backup

If $\langle \phi_1 \rangle \ll \langle \phi_2 \rangle$

$a \simeq a_1,\ f_a \simeq v_1$

Class of models of

Babu, Rothstein, Seckel '93

Correct relic abundance + stable for a high-scale $\langle \phi_1 \rangle$

The origin of matter: Dark Matter

$T_{\mathrm{RH}} > \langle \phi_2 \rangle \gg \langle \phi_1 \rangle$ Post-inflationary scenario $\mathcal{L} \supset \frac{a}{v_1} M_N N^c N$

Majoron **thermalizes** via **RH neutrinos**, in thermal equilibrium via Z'

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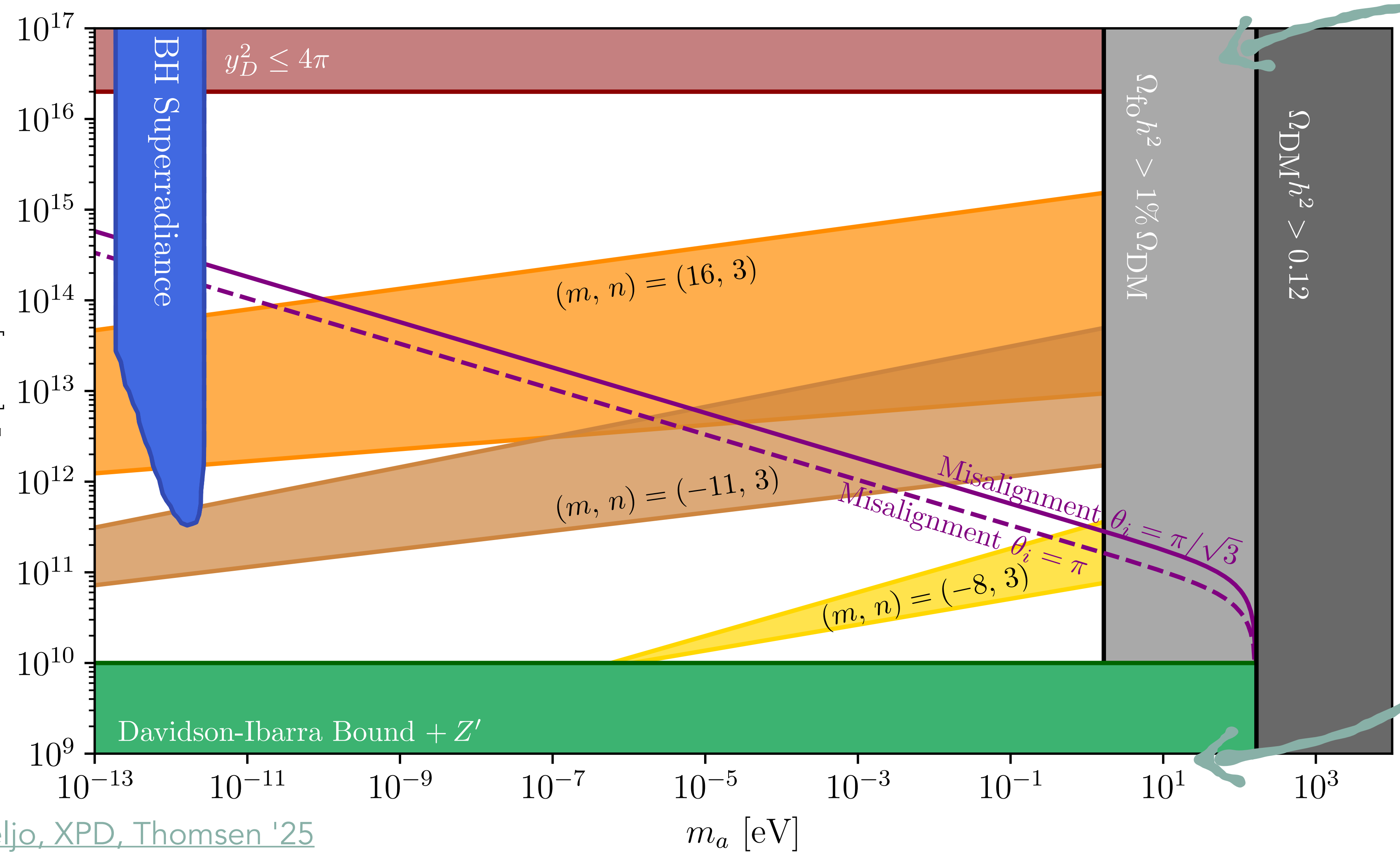

Greljo, XPD, Thomsen '25

Hot DM contribution too large for CMB measurements

$M_{N_1} \gtrsim 4.9 \times 10^8$ GeV

+ Z' decoupling

The origin of matter: Dark Matter

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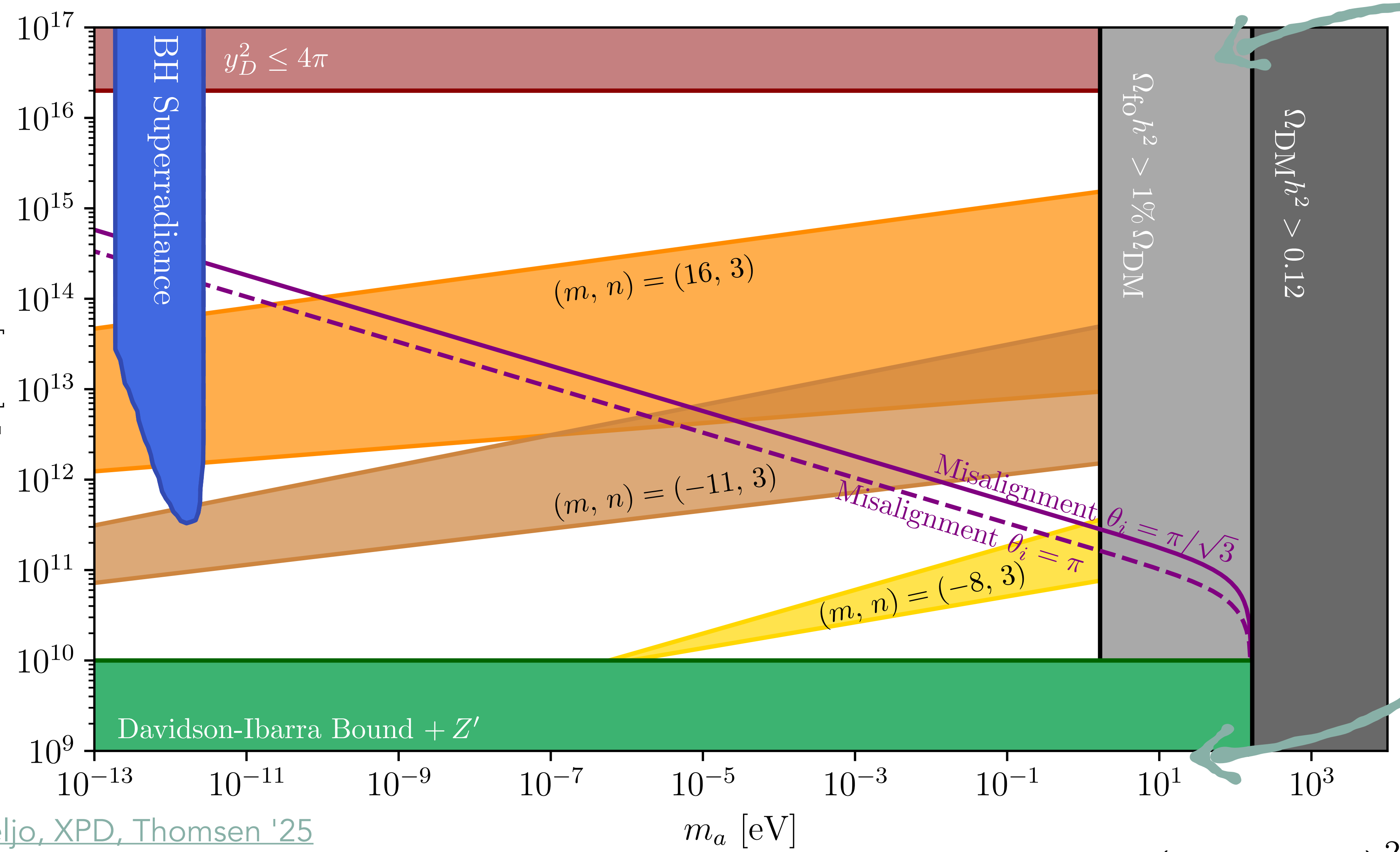

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$\theta_i = \sqrt{\langle\theta_i^2\rangle} = \pi/\sqrt{3}$

Misalignment mechanism: $\Omega_{\rm DM} h^2 \simeq 0.12 \left(\frac{\theta_i f_a}{1.9\times10^{13}}\right)^2 \left(\frac{m_a}{1\,\mu\rm eV}\right)^{1/2} \left(\frac{90}{g_*(T_{\rm osc})}\right)^{1/4}$.

Testable! $\Delta N_{\rm eff} = 0.027$ [CMB-S4 sensitivity 0.0156] Arias, Cadamuro, Goodsell, Jaeckel, Redondo, Ringwald '12

The origin of matter: Dark Matter

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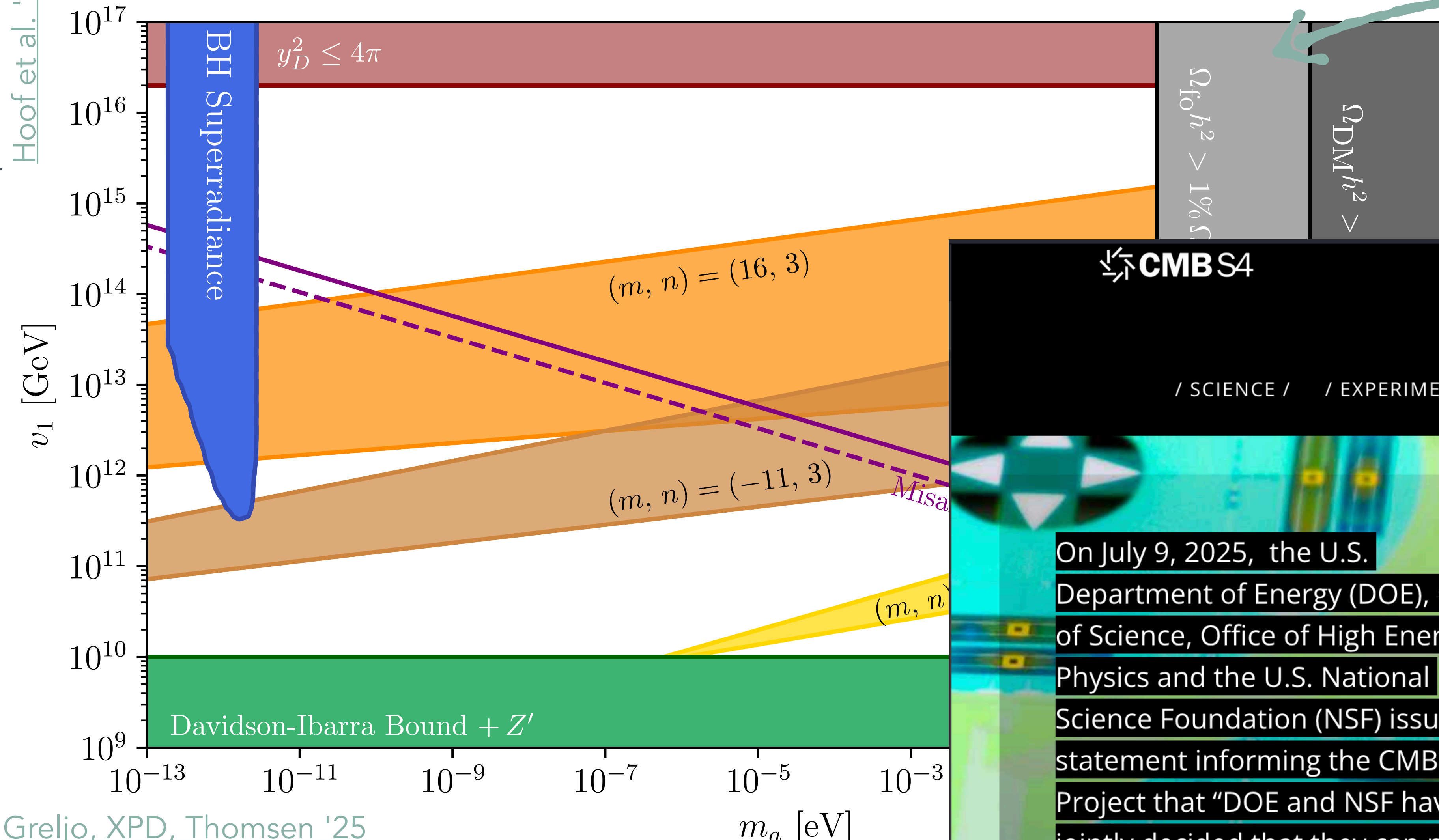
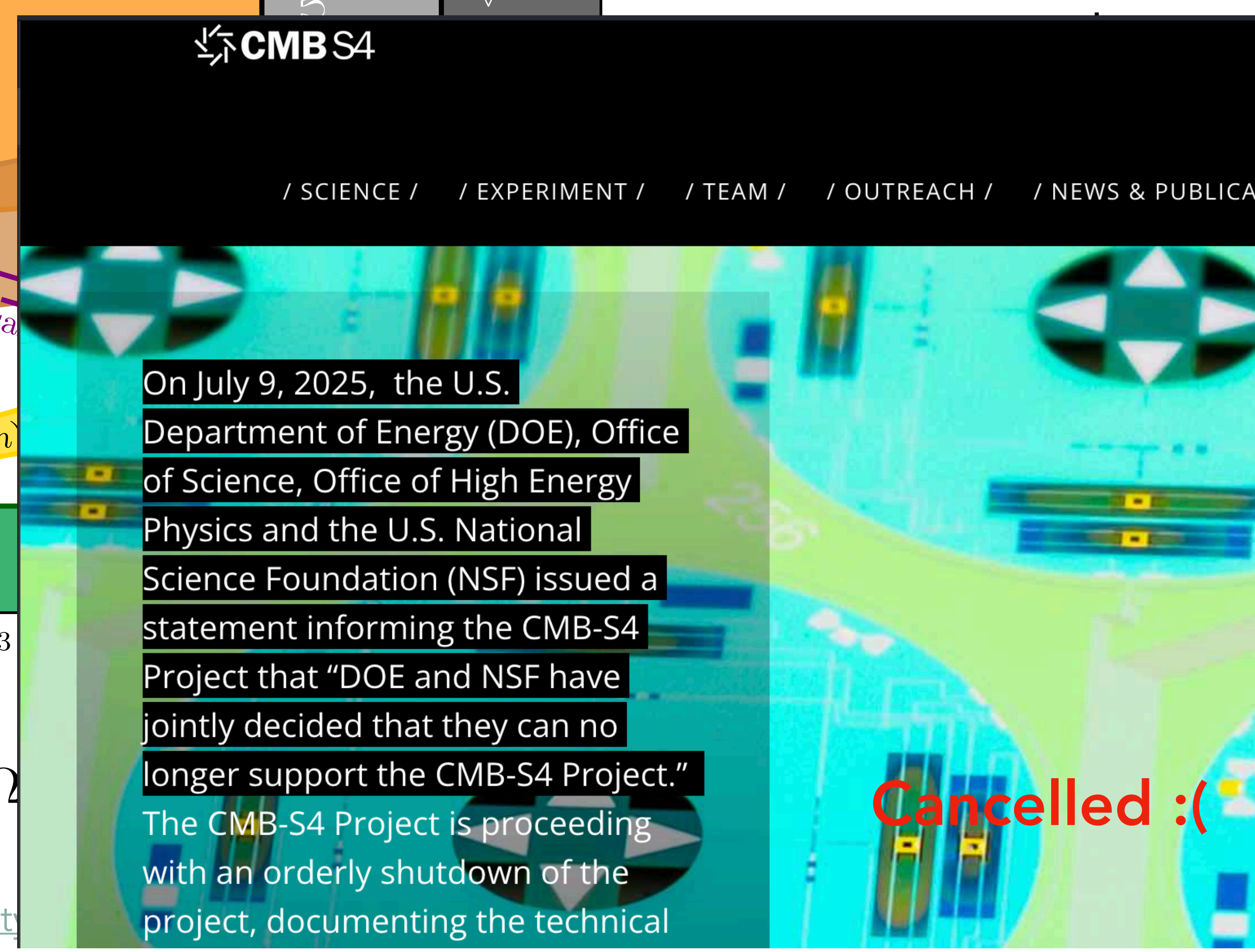


Hot DM contribution too large for CMB

Greljo, XPD, Thomsen '25

Misalignment mechanism: Ω



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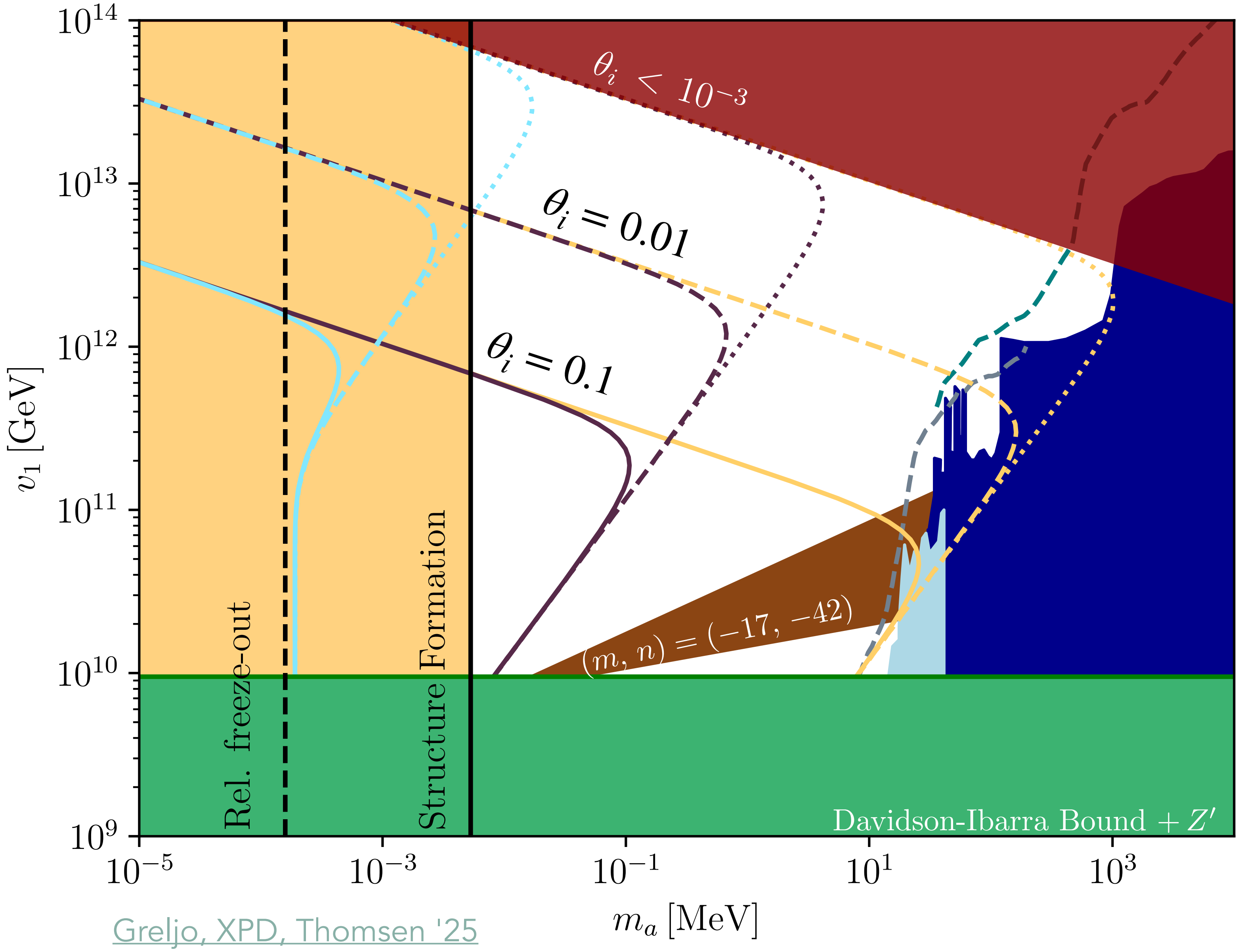
The origin of matter: Dark Matter

$\langle \phi_1 \rangle \simeq T_{\rm RH} > M_{N_1} = \frac{\langle \phi_1 \rangle^2}{\langle \phi_2 \rangle}$ Pre-inflationary scenario: symmetry never restored

N_1 in thermal equilibrium (strong washout ℓHN-interactions or Z')



Greljo, XPD, Thomsen '25

Structure formation bound: Iršič et al. '17

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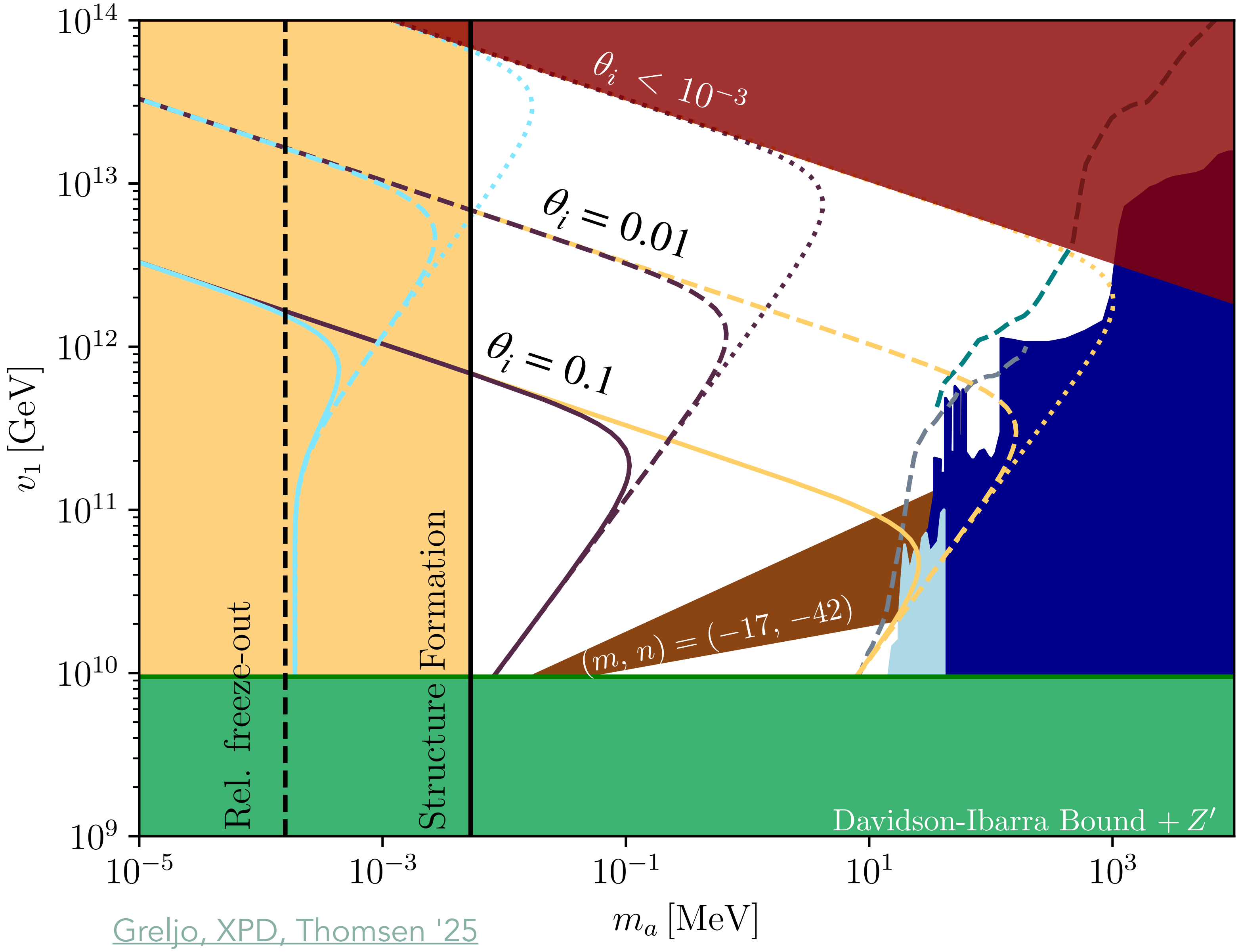

Greljo, XPD, Thomsen '25

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Freeze-in via RH neutrinos

$N_1 N_1 \to aa$

+ misalignment

θ_i can take any value

Effective Yukawa: $M_{N_1}/v_1 = v_1/v_2$

$v_1/v_2 = 0.001,\ 0.01\ ,\ 0.1$

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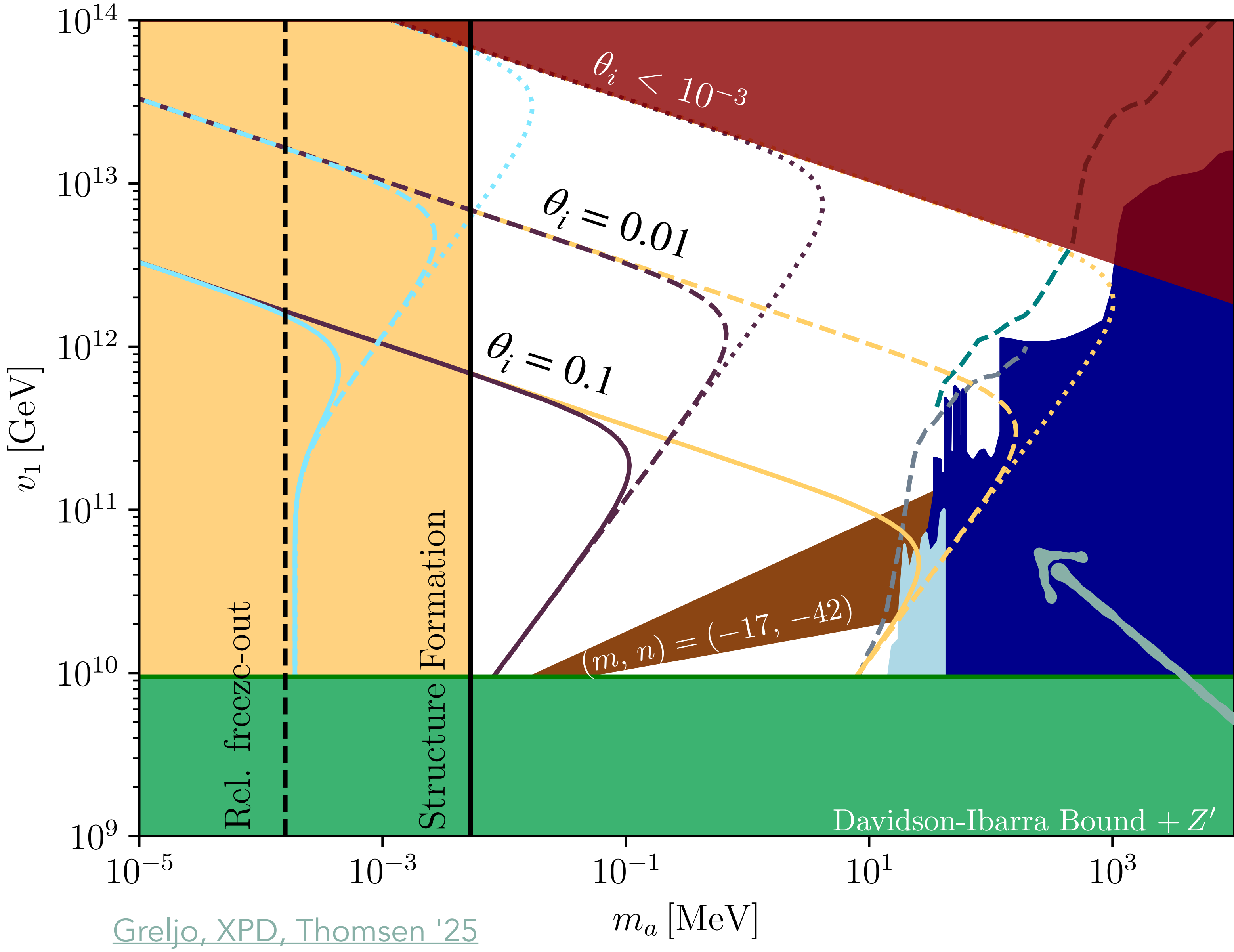

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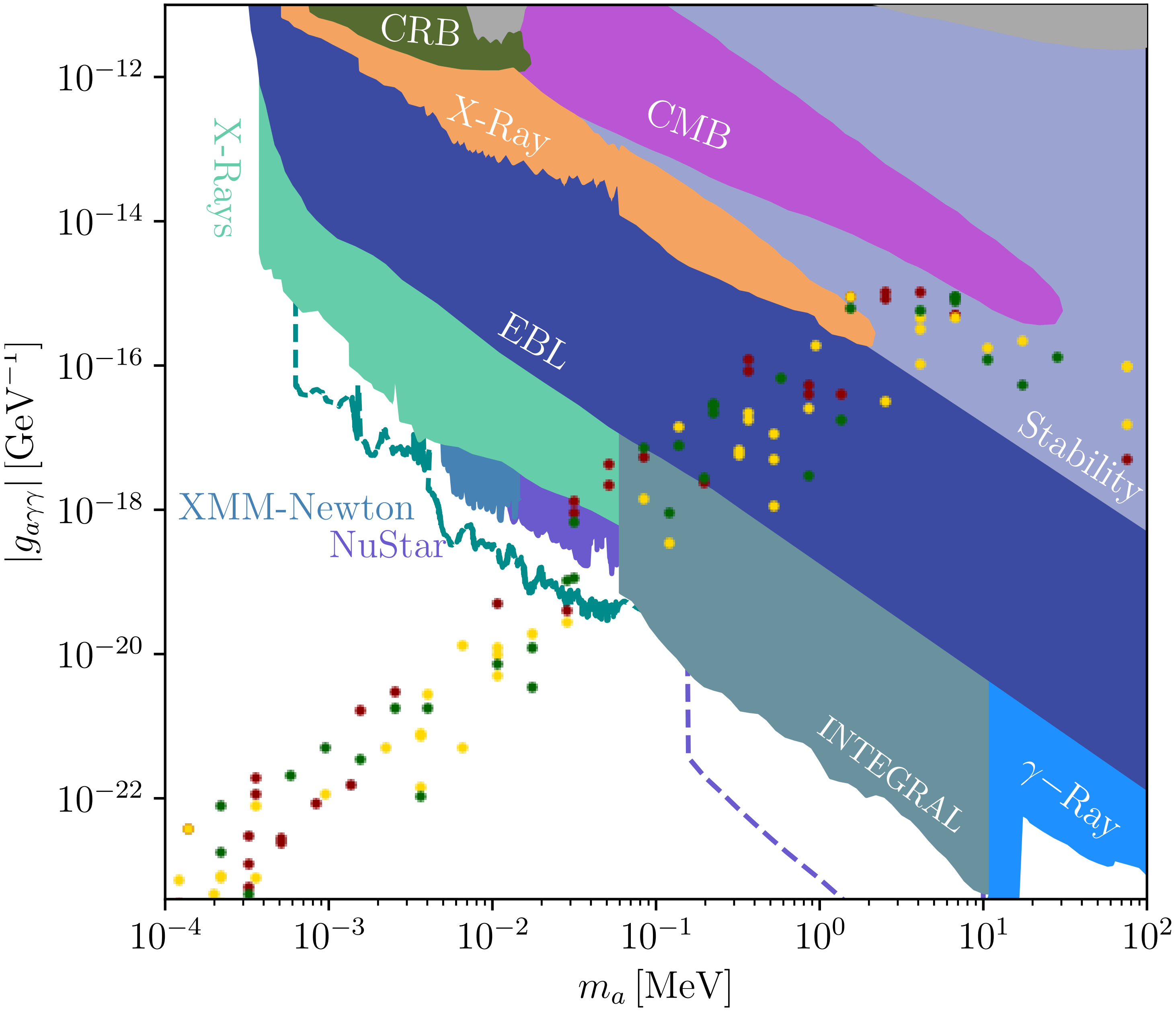
Neutrino telescope searches

Garcia-Cely, Heeck '17,
Akita, Niibo '22

Future experiments: JUNO & HK

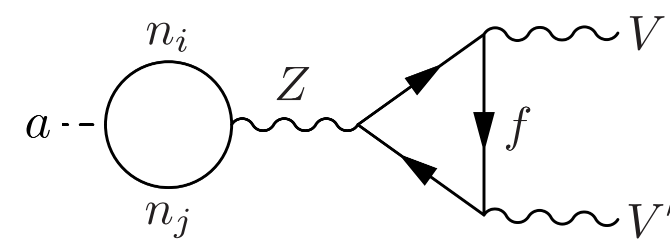
Dark Matter Searches

Greljo, XPD, Thomsen '25



Heeck, Patel '19

$$\mathcal{L} \supset \frac{m_a^2}{(16\pi)^2 v_1} h\left(\frac{m_a^2}{4m_f^2}\right) a F\widetilde{F}$$



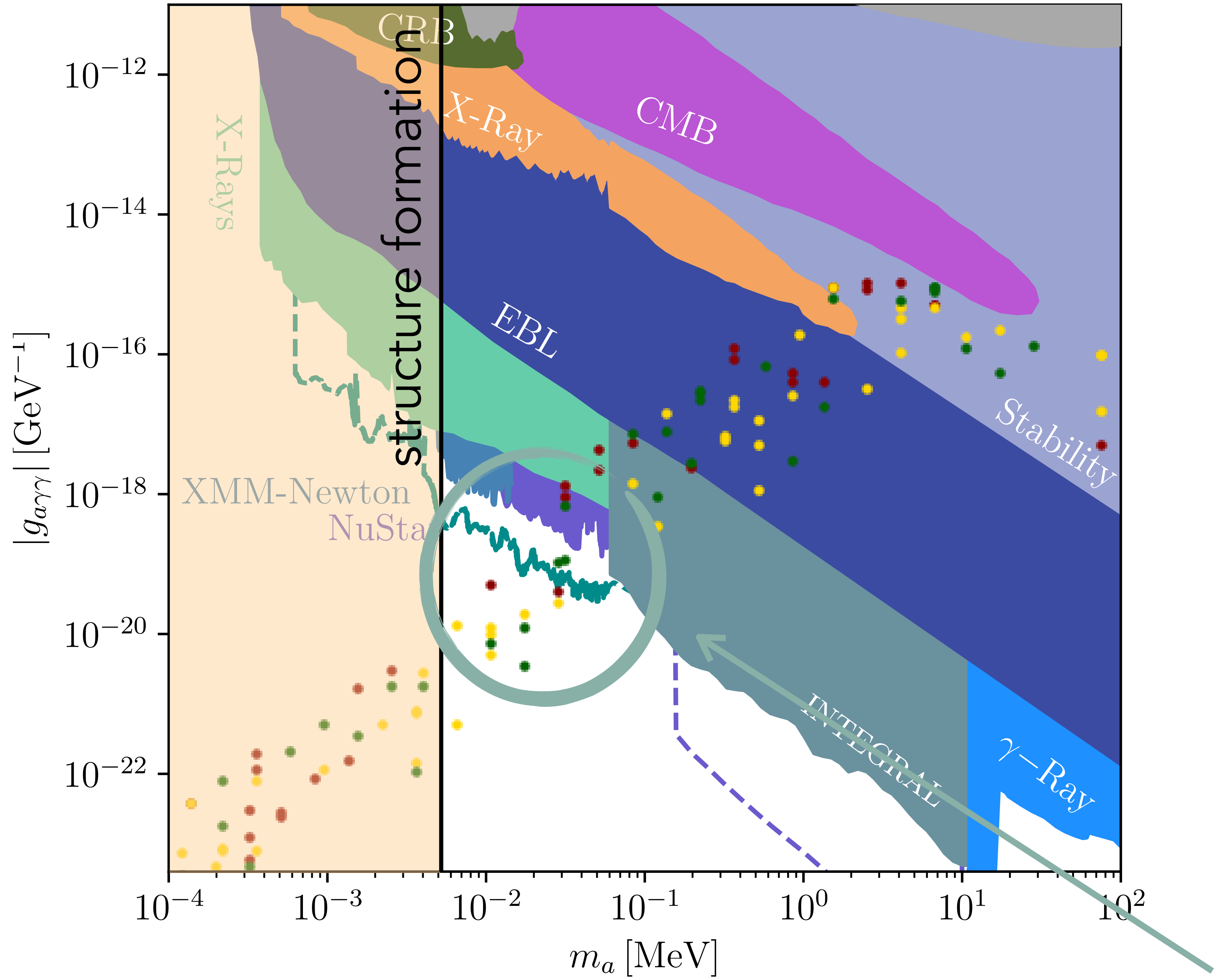
photon DM searches constrain the model to masses lower than $m_a \lesssim 0.1\text{MeV}$

bounds from: Cadamuro, Redondo '11, Langhoff, Outmezguine, Rodd '22, O'Hare Github

prospects from: THESEUS '20, GammaTPC '25

Dark Matter Searches

Greljo, XPD, Thomsen '25



Heeck, Patel '19

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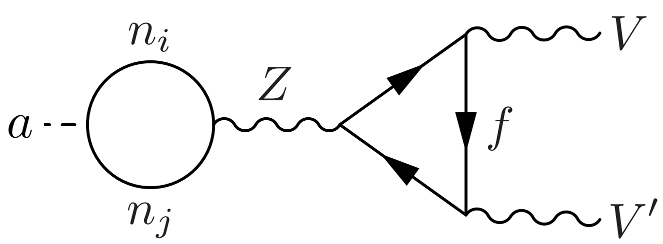

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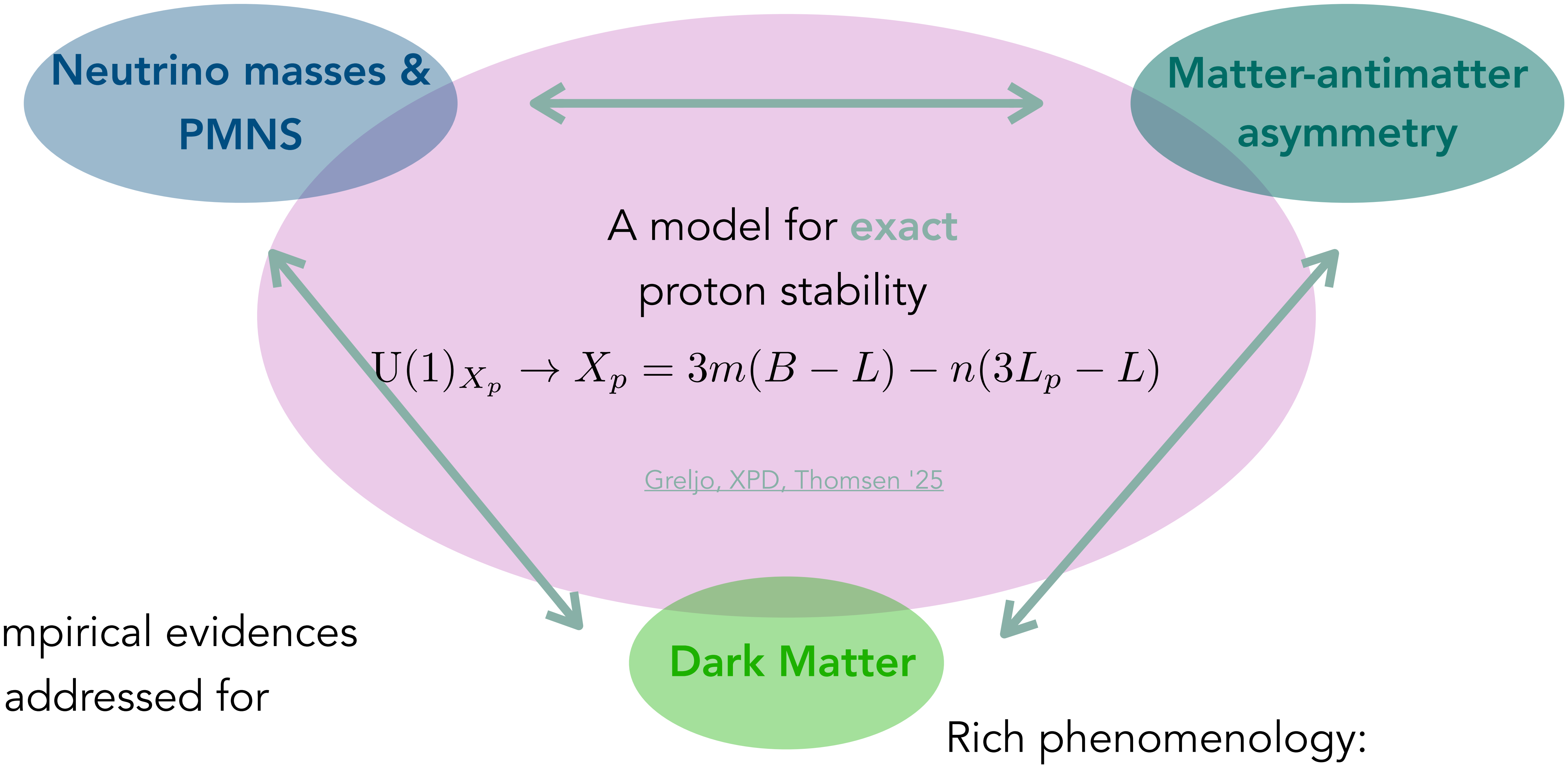
Future $\gamma-$ and $X-$ray telescopes are **sensitive** to further test the majoron ``thermal window".

Conclusions



All empirical evidences addressed for

$$\langle \phi_1 \rangle \sim 10^{10-14}\,\mathrm{GeV}$$

Rich phenomenology:

- $0\nu\beta\beta$ & δ_{CP}
- γ and X-ray telescopes, ΔN_{eff}
- no proton decay :)

Conclusions

Neutrino masses & PMNS

Matter-antimatter asymmetry

A model for **exact** proton stability

$$\mathrm{U}(1)_{X_p} \to X_p = 3m(B-L) - n(3L_p - L)$$

Greljo, XPD, Thomsen '25

Dark Matter

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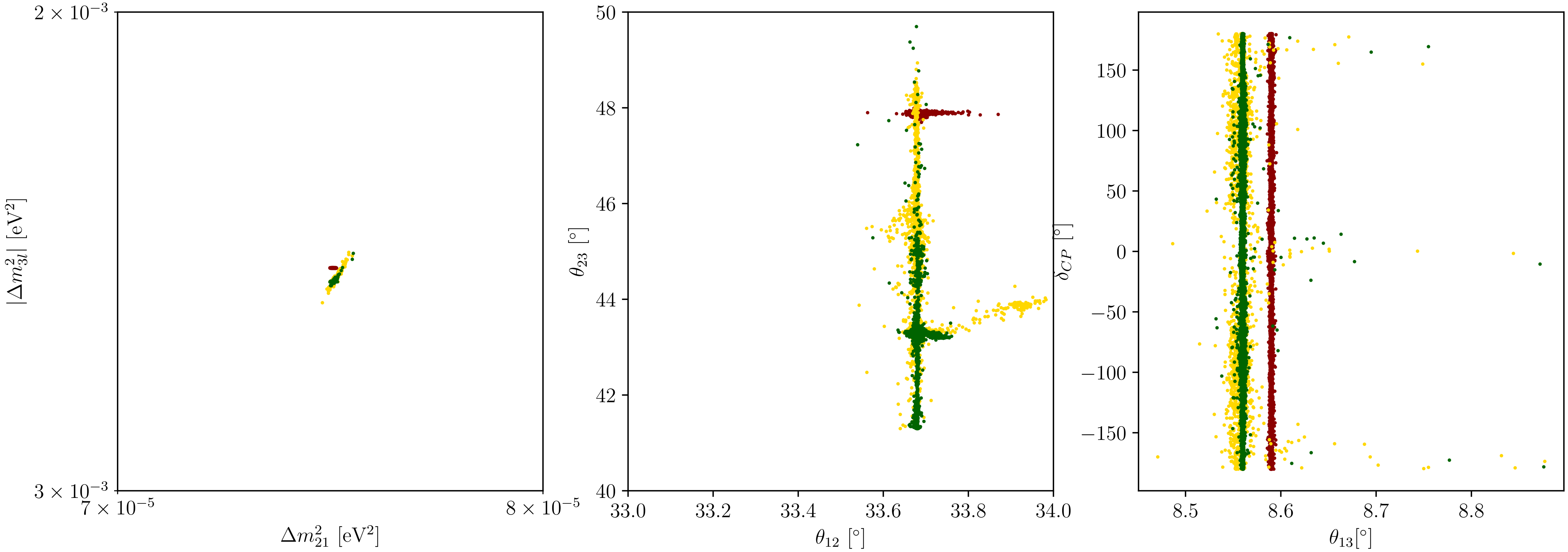
Thank you for your attention!

Back Up

Parameter Scan

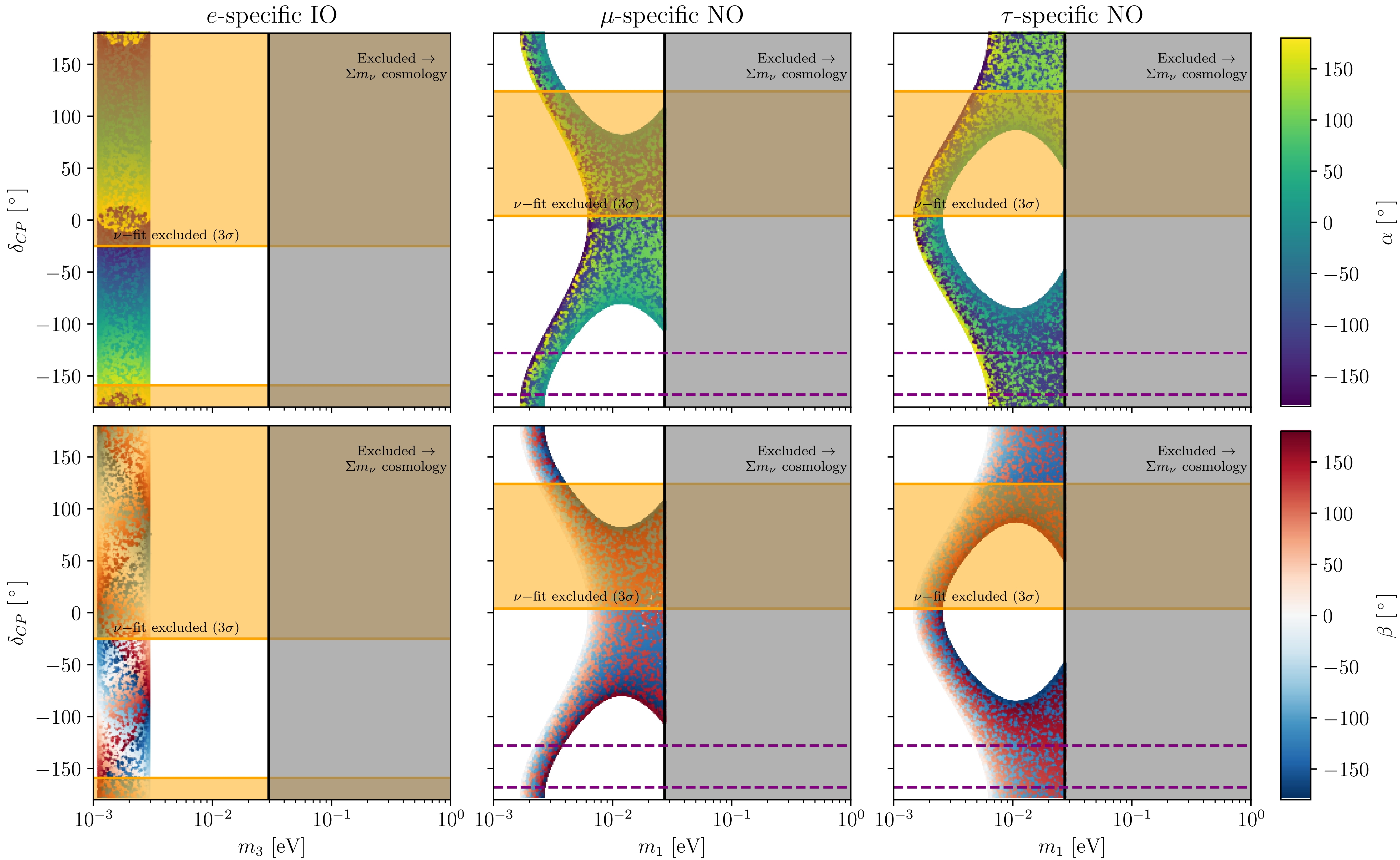


We leave δ_{CP} unconstrained

Nu-fit 6.0 '24

		Normal Ordering (best fit)		Inverted Ordering ($\Delta\chi^2 = 6.1$)	
		bfp $\pm1\sigma$	3σ range	bfp $\pm1\sigma$	3σ range
IC24 with SK atmospheric data	$\sin^2\theta_{12}$	$0.308^{+0.012}_{-0.011}$	$0.275 \to 0.345$	$0.308^{+0.012}_{-0.011}$	$0.275 \to 0.345$
	$\theta_{12}/°$	$33.68^{+0.73}_{-0.70}$	$31.63 \to 35.95$	$33.68^{+0.73}_{-0.70}$	$31.63 \to 35.95$
	$\sin^2\theta_{23}$	$0.470^{+0.017}_{-0.013}$	$0.435 \to 0.585$	$0.550^{+0.012}_{-0.015}$	$0.440 \to 0.584$
	$\theta_{23}/°$	$43.3^{+1.0}_{-0.8}$	$41.3 \to 49.9$	$47.9^{+0.7}_{-0.9}$	$41.5 \to 49.8$
	$\sin^2\theta_{13}$	$0.02215^{+0.00056}_{-0.00058}$	$0.02030 \to 0.02388$	$0.02231^{+0.00056}_{-0.00056}$	$0.02060 \to 0.02409$
	$\theta_{13}/°$	$8.56^{+0.11}_{-0.11}$	$8.19 \to 8.89$	$8.59^{+0.11}_{-0.11}$	$8.25 \to 8.93$
	$\delta_{\mathrm{CP}}/°$	212^{+26}_{-41}	$124 \to 364$	274^{+22}_{-25}	$201 \to 335$
	$\frac{\Delta m^2_{21}}{10^{-5}\ \mathrm{eV}^2}$	$7.49^{+0.19}_{-0.19}$	$6.92 \to 8.05$	$7.49^{+0.19}_{-0.19}$	$6.92 \to 8.05$
	$\frac{\Delta m^2_{3\ell}}{10^{-3}\ \mathrm{eV}^2}$	$+2.513^{+0.021}_{-0.019}$	$+2.451 \to +2.578$	$-2.484^{+0.020}_{-0.020}$	$-2.547 \to -2.421$

Parameter Scan



Triangle equations

Different scenarios: $p = \{e, \mu, \tau\}$

$$\frac{e^{i(\alpha+\beta+2\delta_{\rm CP})}}{m_1 m_2 m_3}[m]_{11} = \frac{1}{m_3} s_{13}^2 + \frac{e^{i(\beta+2\delta_{\rm CP})}}{m_2} s_{12}^2 c_{13}^2 + \frac{e^{i(\alpha+2\delta_{\rm CP})}}{m_1} c_{12}^2 c_{13}^2$$

$$\frac{e^{i(\alpha+\beta)}}{m_1 m_2 m_3}[m]_{22} = \frac{1}{m_3} c_{13}^2 s_{23}^2 + \frac{e^{i\beta}}{m_2}\left(c_{12}c_{23} - s_{23}s_{12}s_{13}e^{i\delta_{\rm CP}}\right)^2 + \frac{e^{i\alpha}}{m_1}\left(s_{12}c_{23} + c_{12}s_{23}s_{13}e^{i\delta_{\rm CP}}\right)^2$$

$$\frac{e^{i(\alpha+\beta)}}{m_1 m_2 m_3}[m]_{33} = \frac{1}{m_3} c_{13}^2 c_{23}^2 + \frac{e^{i\beta}}{m_2}\left(c_{12}s_{23} + c_{23}s_{12}s_{13}e^{i\delta_{\rm CP}}\right)^2 + \frac{e^{i\alpha}}{m_1}\left(s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta_{\rm CP}}\right)^2$$

EW-running of the Weinberg operator

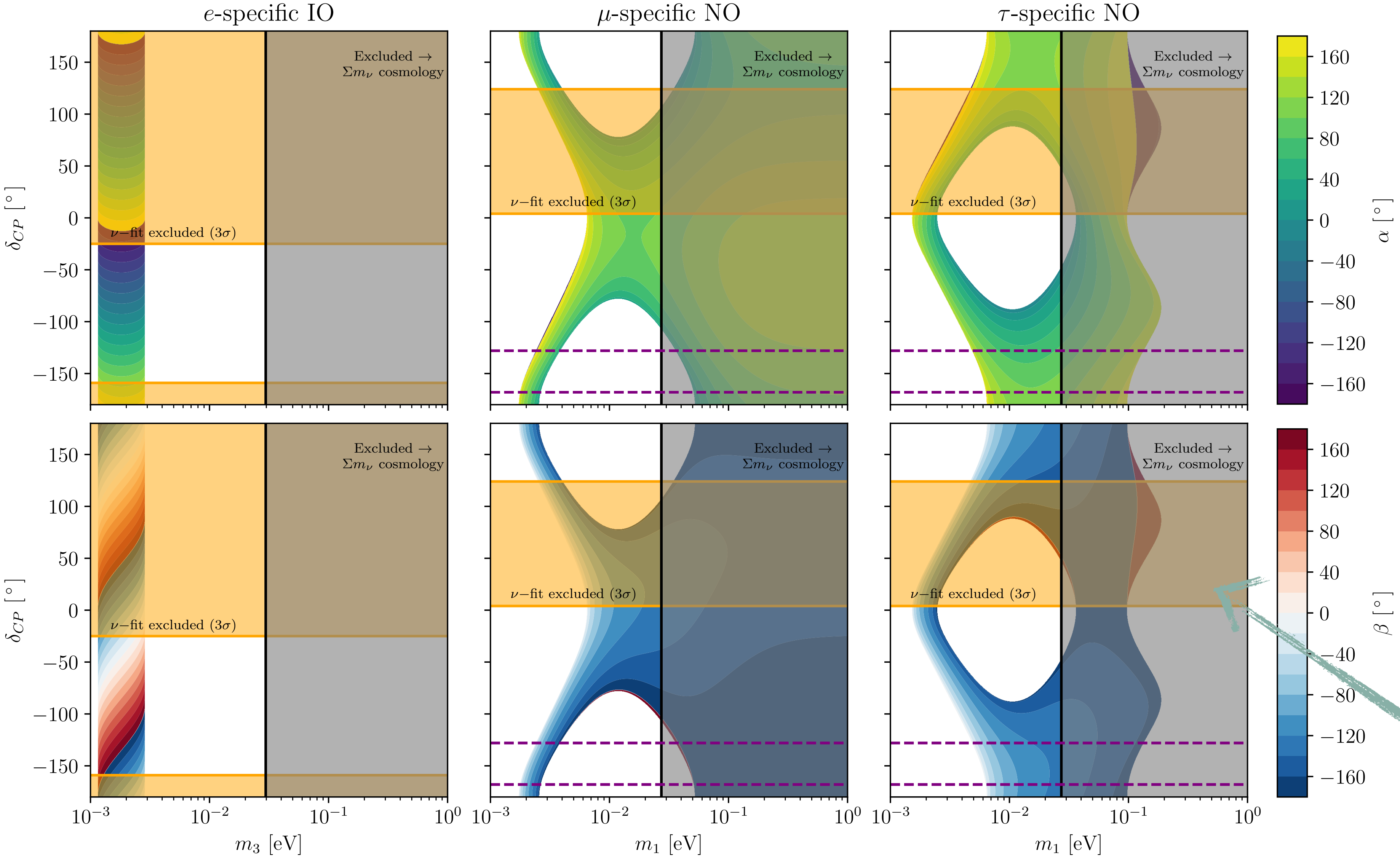
$$\begin{aligned}[m_\nu^*]_{pp} &= \det\left(-v_{\rm EW}^2 Y A_{\rm eff} Y^\intercal\right) \\ &\simeq -\gamma\, t \det\left(v_{\rm EW}^2 Y M^{-1} Y^\intercal\right)\end{aligned}$$

$$\gamma = \frac{1}{16\pi^2}\left(2\lambda + \frac{1}{2}g_1^2 - \frac{3}{2}g_2^2\right) \qquad t = \log\left(\sqrt{M_{N_2}M_{N_3}}/M_{N_1}\right)$$

Numerical estimate

$$|[m_\nu]_{pp}| \overset{?}{\lesssim} 0.01 \cdot \begin{cases} m_2 m_3 & \text{(NO)} \\ m_1 m_2 & \text{(IO)} \end{cases}.$$

One-loop correction



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Freeze-in majoron

$\mathrm{t-channel}: N_1 N_1 \to aa$

Reach thermal equilibrium, and freezes-out relativistically

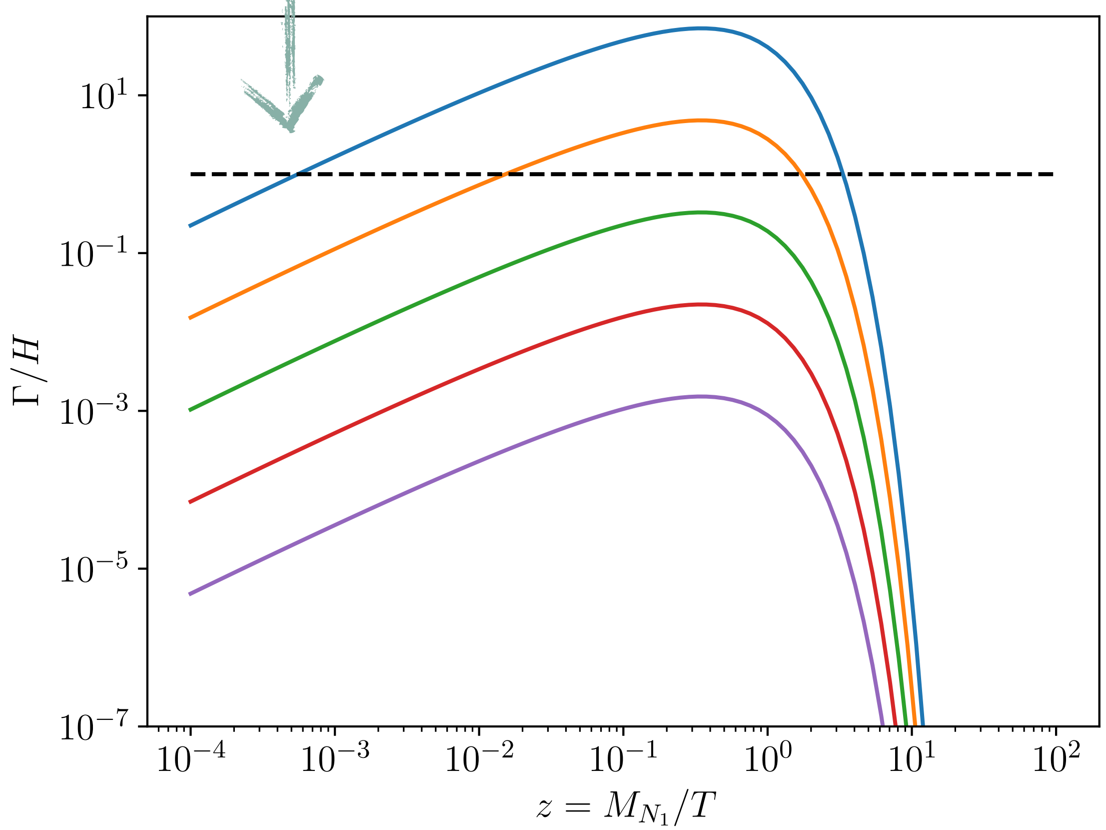
$$\Omega_{\rm fo}h^2 = \frac{\zeta(3) g_s(T_0) m_a T_0^3}{\pi^2 g_s(T_{\rm dec})\rho_c} h^2 = 0.12 \frac{m_a}{166.62\,\mathrm{eV}} \frac{106.75}{g_s(T_{\rm dec})},$$

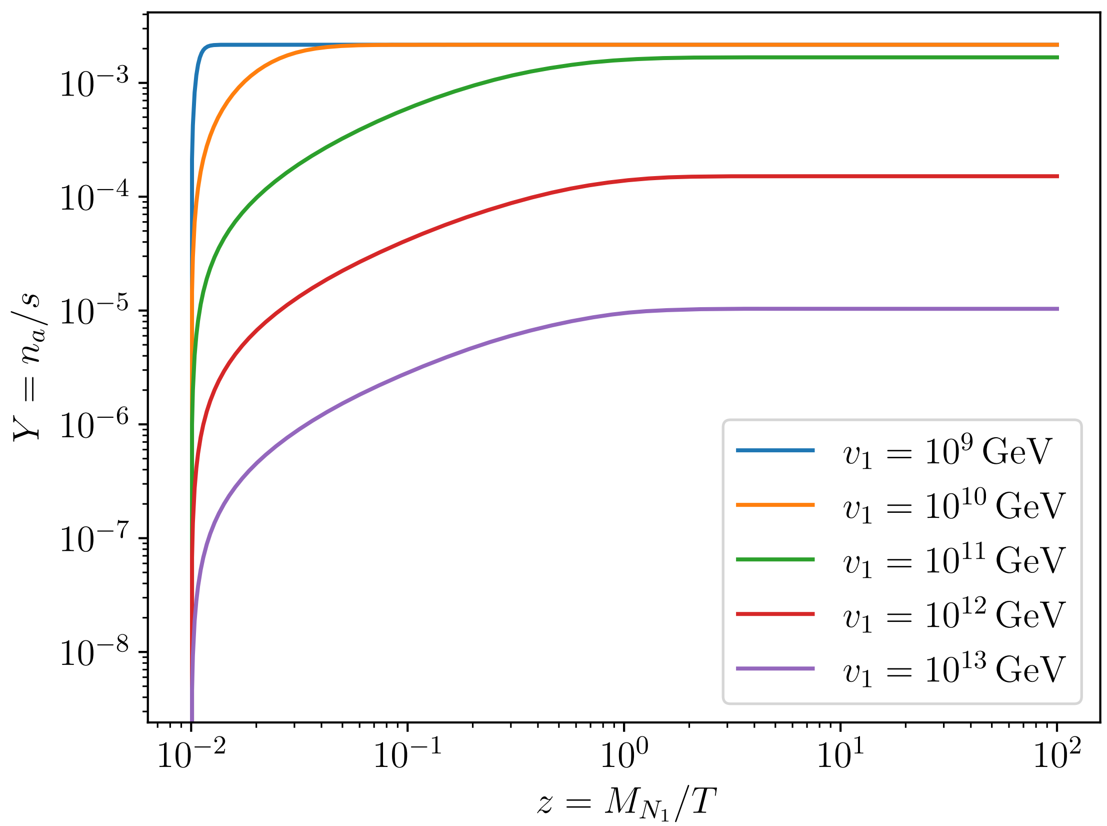
Gu, Sarkar'09,
Hambye, Frigerio, Masso '11
Boulebnane, Heeck, Nguyen, Teresi '17

$$\gamma_{\rm ann.} = N_a \frac{T}{64\pi^4}\int_{4M_N^2}^{\infty} ds\, \hat\sigma(s)\, \sqrt{s}\, K_1\left(\frac{\sqrt{s}}{T}\right)$$

Freeze-in: $$zHs\frac{dY}{dz} = \gamma_{\rm ann}\left(1-\frac{Y^2}{Y_{\rm eq}^2}\right)$$

$$\hat\sigma(a\,b\to 1\,2) = \frac{g_a g_b}{c_{ab}} \frac{2\left[\left((s-m_a^2-m_b^2)^2-4m_a^2m_b^2\right)\right]}{s}\sigma(s)$$

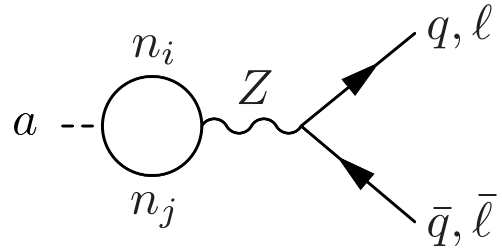




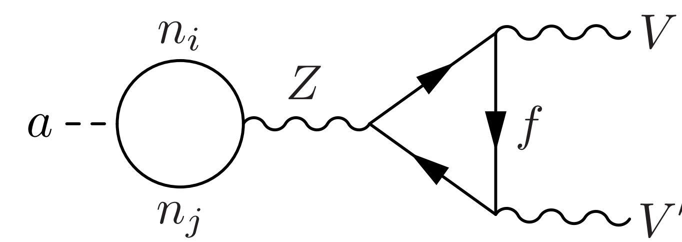
Dark Matter Searches

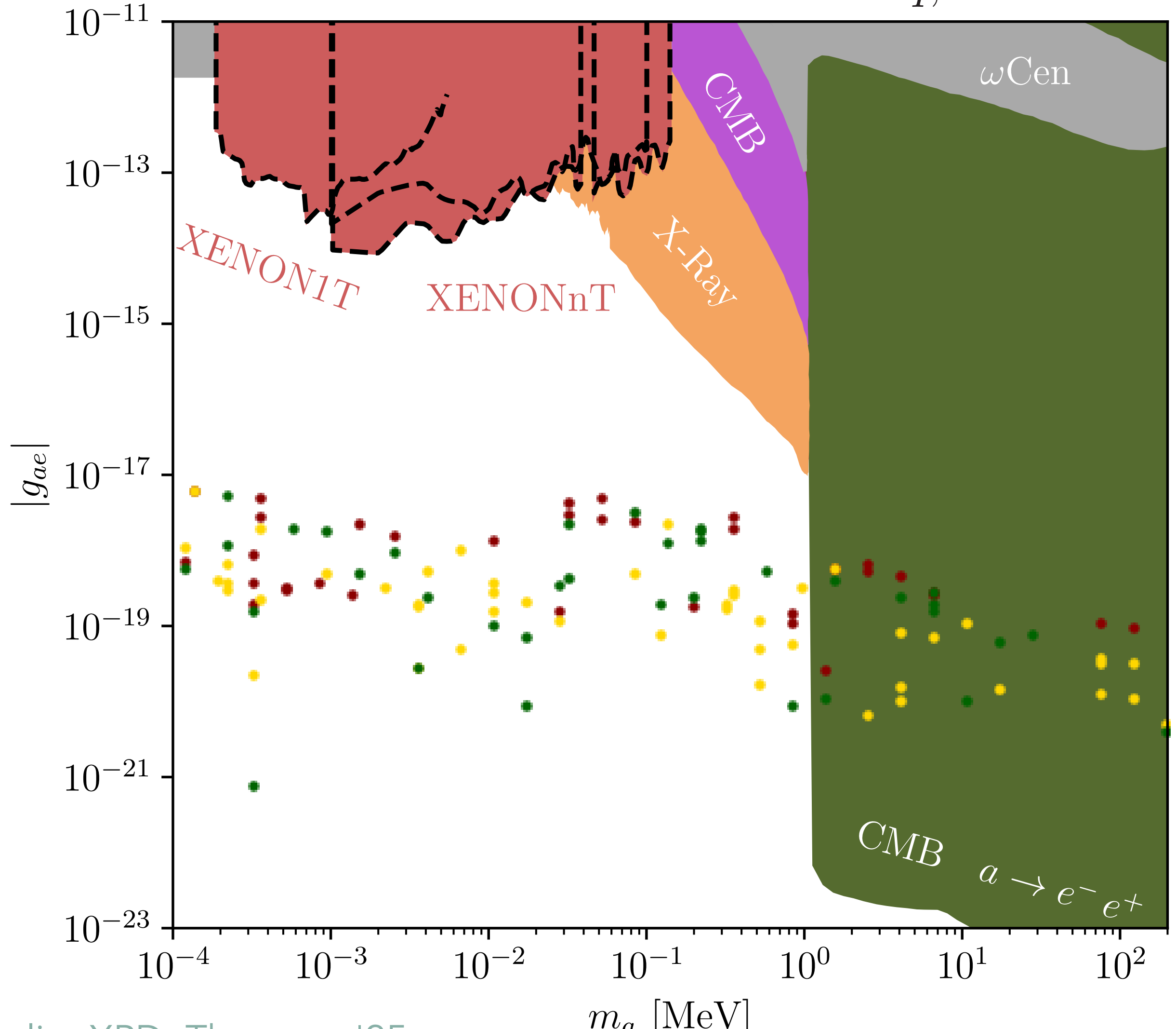
Heeck, Patel '19

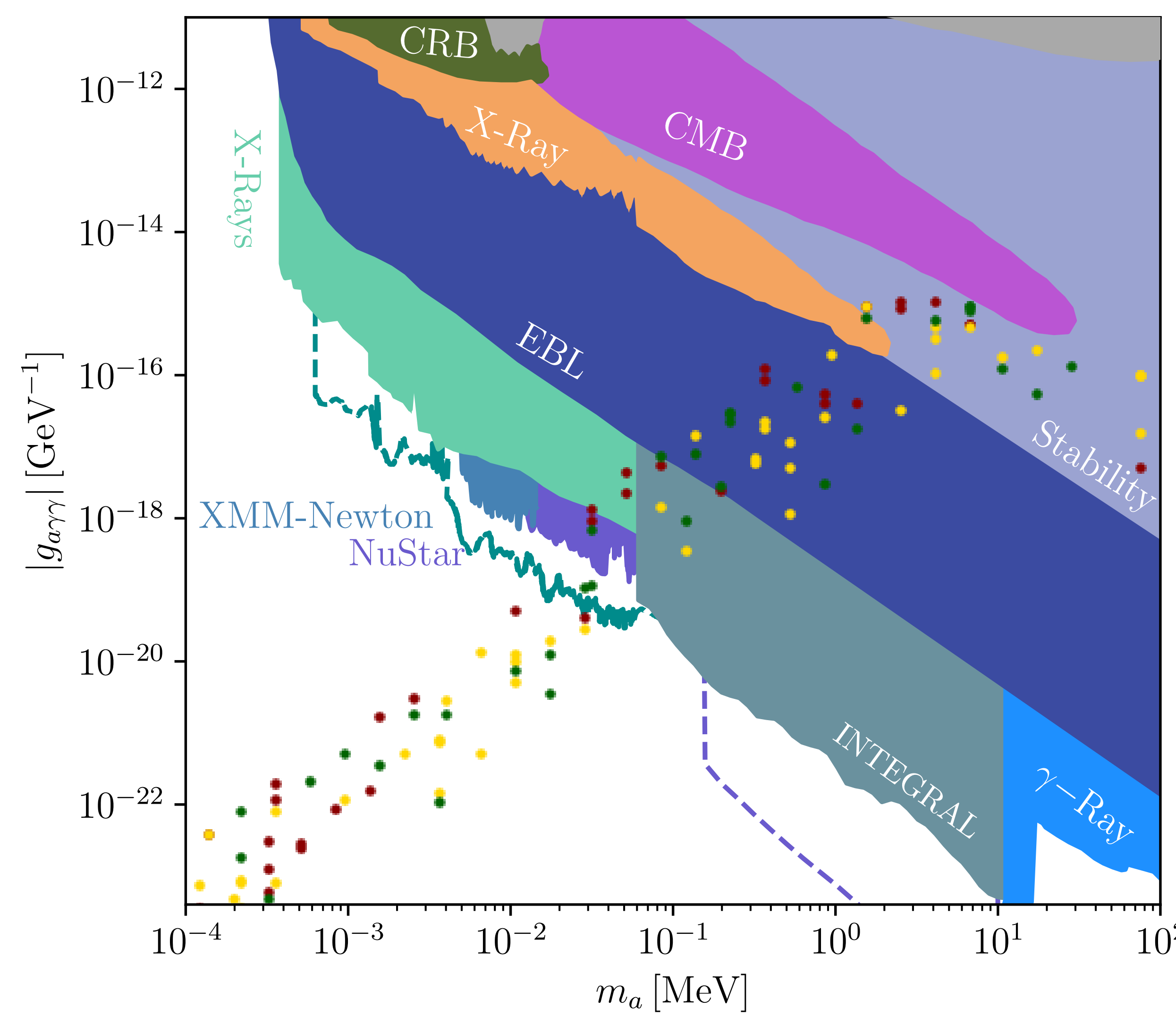
$$\mathcal{L} \supset \frac{m_e}{16\pi v_1} a\,\bar{e}\gamma_5 e$$



$$\mathcal{L} \supset \frac{m_a^2}{(16\pi)^2 v_1} h\left(\frac{m_a^2}{4m_f^2}\right) a F\widetilde{F}$$







Greljo, XPD, Thomsen '25

Electron and photon DM searches constrain the model to lower masses $m_a \lesssim 0.1\mathrm{MeV}$

Future $\gamma-$ and $X-$ray telescopes are **sensitive** to further test this scenario

Cosmological History

T

$\langle\phi_2\rangle$ — Local strings

$\langle\phi_1\rangle$ — Global strings

M_{N_1} — Leptogenesis

$T \sim \sqrt{M_{\rm Pl} m_a}$
$m_a \sim H(T)$ — Misalignment & Domain wall-string network

Post-inflationary

$T_{\rm RH} > \langle\phi_2\rangle$ Local + global strings + DW

$T_{\rm RH} > \langle\phi_1\rangle$ Global strings + DW

Pre-inflationary

$\langle\phi_1\rangle \gtrsim T_{\rm RH}$ Bounds from isocurvature

Domain Wall Problem?

$\mathrm{U}(1)_{B-L} \rightarrow \mathbb{Z}_N$

$$V_{\rm grav} = |\eta|(4\pi M_{\rm Pl}^2)^2 \times \left(\frac{v_1}{\sqrt{2}M_{\rm Pl}}\right)^{|s|} \left(\frac{v_2}{\sqrt{2}M_{\rm Pl}}\right)^{|t|} \cos\left(\alpha_\eta - 9\frac{st}{k_b}\frac{a}{f_a}\right),$$

Domain Wall Problem?

Winding numbers of the strings

$$\mathcal{E}_{\rm kin} \sim \int \mathrm{d}^2x \, |\partial_i \bar{\phi}_1'|^2 \quad \text{with} \quad \bar{\phi}_1'(\theta) \sim \frac{1}{\sqrt{2}} v_1 e^{i\theta(w_1 - w_2 \mathcal{X}_1/\mathcal{X}_2)}$$

scalar charges

$$\mathcal{E}_{\rm kin} \sim |w_1 \mathcal{X}_2 - w_2 \mathcal{X}_1| = \min_{w \in \mathbb{Z}} |w \mathcal{X}_2 - w_2 \mathcal{X}_1| \to |s w_1 + t w_2| = \min_{w \in \mathbb{Z}} |s w + t w_2|$$

$$V_{\rm grav.}(\bar{\phi}_1, \, \bar{\phi}_2) \to V_{\rm grav.}(v_1, v_2) \cos(s w_1 \, \theta + t w_2 \, \theta) \, .$$

$$N_W = \left| s w_1 + t w_2 \right|$$

- local strings: $N_W = \min_{w \in \mathbb{Z}} |sw + t|$,
- global strings: $N_W = |s|$.

Automatic solution if $N_W = 1$ Barr, Seckel '92

Domain Wall Problem?

$$N_W = \left|sw_1 + tw_2\right|$$

Automatic solution if $N_W = 1$

- local strings: $N_W = \min_{w\in\mathbb{Z}} |sw + t|$,
- global strings: $N_W = |s|$.

		b										
		-5	-4	-3	-2	-1	0	1	2	3	4	5
a	-5		15		17		19				23	
	-4	7		6	13	7	15	8	17	9	19	10
	-3		11		9		11		13		15	
	-2	7	11	4		3	7	4	9		13	8
	-1		11		5				7		13	
	0	7	11	4	5				7	5	13	8
	1		11		7		5		7		13	
	2		13	6	11	5	9	4		5	13	8
	3		17				13		11		13	
	4	11	21	10	19	9	17	8	15	7		8
	5		25		23		21		19		17	

Green: $|s| = 1$

Blue: $N_W = \min_{w\in\mathbb{Z}} |sw + t|$

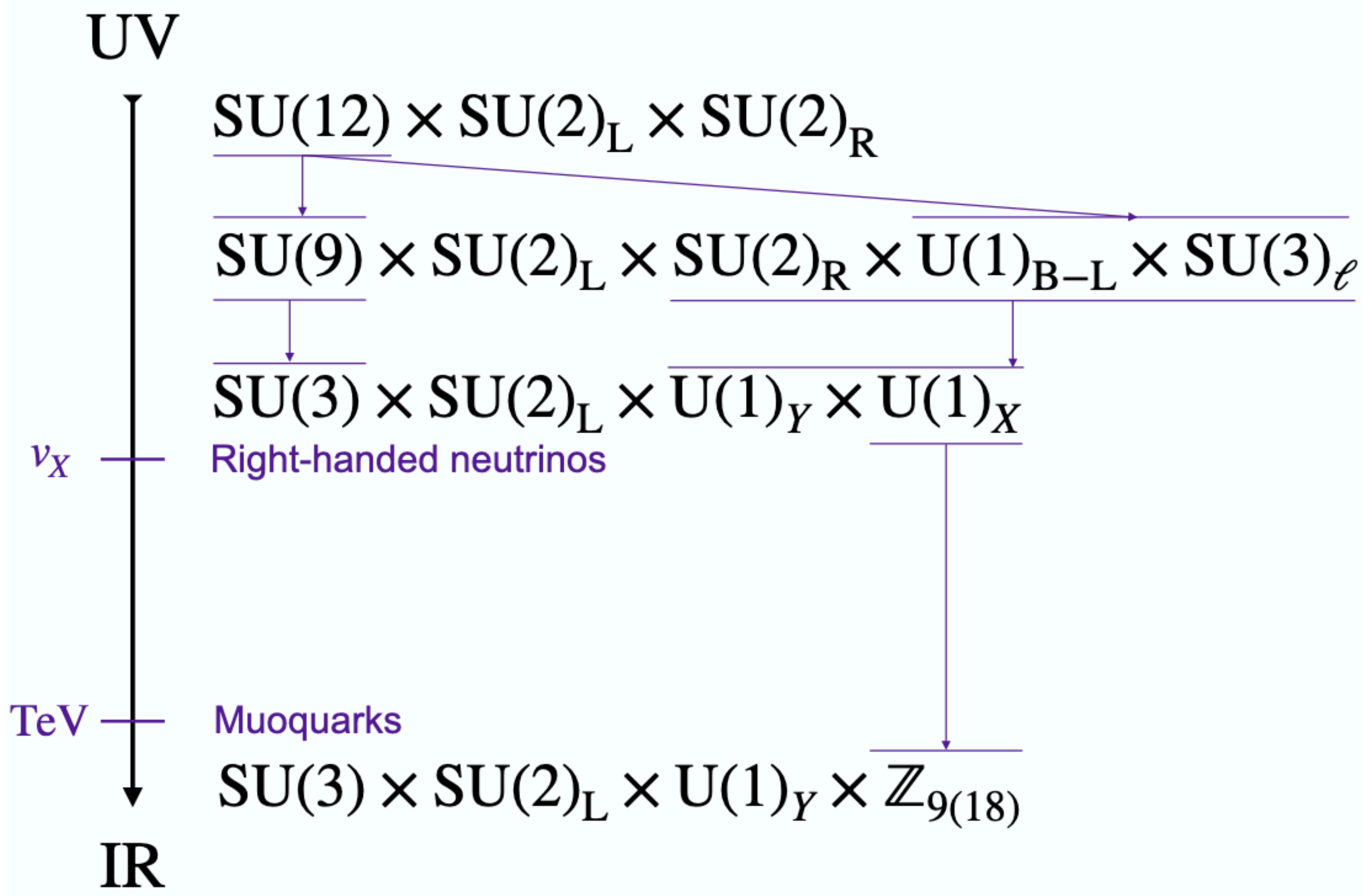
Automatic solution of a Domain Wall problem via the charges of the model.

Criticism to this type of models from Lu, Reece, Sun '23

A Unification Path

Davighi, Greljo, Thomsen '22

$$\Psi_L \sim (\mathbf{12},\, \mathbf{2},\, \mathbf{1}) \quad \Psi_R \sim (\mathbf{12},\, \mathbf{1},\, \mathbf{2})$$



Tentative flavour-gauge unification